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Re-Design and Fabrication of Titanium Multi-Wall Thermal Protection System (TPS) Test Panels

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FOREWORD

This is an interim report on work being performed by Rohr Industries -- Design and Fabrication of Titanium Multiwall Thermal Protection System (TPS) -- describing the Task VI activities. In Task VI, the Task I panel was redesigned to incorporate ninety degree side closures, Ti-6Al-2Sn-4Zr-2Mo upper surface, larger nodes on the dimpled sheets, and through panel fasteners. Structural and thermal analyses were performed. Tools were designed and fabricated. Specimens were fabricated and tested to verify the design analysis. An array of twenty, an array of two, and two additional titanium multiwall panels were delivered to NASA Langley Research Center for testing.

This program is administrated by the National Aeronautics and Space Administration, Langley Research Center (NASA LaRC). Mr. John Shideler of the Aerothermal Loads Branch, Loads and Aeroelasticity Division, is the technical monitor.

The following Rohr personnel were the principal contributors to the program during this reporting period: Winn Blair, Program Manager; Dale Jennings, Manufacturing Technology; John E. Meaney, R&D Structures, H. A. Rosenthal, R&D Thermal; D. Timms, Preliminary Design; and L. A. Wiech, Engineering Laboratory. Overall responsibility is assigned to the Rohr Aerospace R&D Engineering organization with U. Bockenhauer, Manager.

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SUMMARY

The titanium multi-wall panel, reported in References 1 and 2 was redesigned to change the side closures angle from 0.524 Rad (30 degrees) to 1.571 Rad (90 degrees) and the dimpled sheet node sizes from 1.5 mm (0.060 inch) to 1.9 mm (0.075 inch). The outer layers of the hot side were changed from Ti-6Al-4V to Ti-6Al-2Sn-4Zr-2Mo. Tests were conducted to verify the structural and thermal performance. One two-panel array was fabricated and delivered to NASA Johnson Space Center for testing in a radiant heating facility. One 20-panel array and two additional panels were delivered to NASA Langley Research Center for testing in the 8-foot High Temperature Structures Facility and the High Intensity Noise Facility. In addition, one panel was fabricated with an internal vacuum.

1/ INTRODUCTION

Rohr Industries was awarded a contract January 1979 to design and fabricate titanium multi-wall thermal protection panels for testing by NASA.

The initial program consisted of the preliminary design of flat panels and tooling, fabrications of flat test panels, and testing in face tension, flexural strength, creep, thermal conductivity, and emittance. Results of these tests were used to design and fabricate a nine-panel array for testing in the Langley Research Center 8-Foot High Temperature Structures Tunnel. A two-panel array was fabricated and delivered to Langley Research Center for vibrational and acoustical tests. A second two-panel array was delivered to Johnson Space Center for radiant heating tests. This design and fabrication effort is documented in References 1 and 2.

One additional part of this program was to determine the extensional, bending and torsional stiffness of flat, multi-wall sandwich. Data for this effort was reported in Reference. 3.

Also a part of this program was to demonstrate that the multi-wall concept could be fabricated as a curved panel. A curved titanium multi-wall panel having a single radius of curvature of 305 mm (12

inches) was fabricated and delivered to NASA Langley Research Center. The panel's overall dimensions were 305 by 305 by 17.2 mm (12 by 12 by 0.680 inches). This was reported in Reference 4.

Another part of the program was to develop a Superalloy Honeycomb-Titanium Honeycomb-Silica Sandwich panel thermal protection concept. This was reported in Reference 5.

In this part of the program the panel described in Reference 2 was redesigned based on an Alternate Thermal Protection System Study, Reference 6, and test results from the nine-panel array, 8-foot High Temperature Structures Tunnel Tests. This report describes the activities of Task VI.

2/ IMPROVEMENTS TO TASK I DESIGN

2.1 DESIGN CHANGES

The Task I design, reported in References 1 and 2, shows a Ti-6Al-4V multiwall panel 17.8 by 304.8 by 304.8 mm (0.7 by 12.0 by 12.0 inches) which has thirty-degree side closures, and clips and tongues as a means for attaching the panel to a vehicle. The design also shows 1.9 mm (0.060 inch) diameter nodes on the dimpled sheets. The thirty-degree side closures presented a tooling problem for LID bonding the panels. Due to the thirty-degree slope, proper pressure could not be applied to that area during the LID bonding cycle, which resulted in poor bonding quality. The original attachment design did not allow for easy removal of panels in any given area of a vehicle.

The new design is based on the Alternate Thermal Protection System Study reported in Reference 6 and evaluation of test results from References 1, 2 and 7. The new design, Figure 1, incorporates 1.571 Rad (90 degrees) side closures, through panel fasteners for easy removal, Ti-6Al-2Sn-2Mo outer sheets for better creep resistance, and 1.9 mm (0.075-inch) diameter nodes for greater strength. The design also allows for smaller, odd shaped transition panels to be made using the same basic tools.

The panel attach bolt design, Figure 2, allows for fibrous insulating material to be placed in the cavity over the attach bolt. This minimizes the heat short from radiation.

2.2 THROUGH PANEL FASTENER DESIGN

The through panel fastener design shown in Figure 2 incorporates the use of a standard bolt and rivnut and a housing that is machined to very thin gauges. This allows for the housing to be filled with insulation, thus keeping the heat transfer to an acceptable level. Panels having these fasteners are easy to install and remove, and permit easy access to any area of the vehicle.

3/ STRUCTURAL ANALYSIS

3.1 DESIGN CRITERIA

The design point for this panel is body point 3140 on the Shuttle vehicle. This point is located on the upper centerline in front of the windshield. The design criteria for this panel consist basically of temperature and aerodynamic pressure. The maximum pressure load is 6.89 KPa (1 psi) ultimate for the ascent case without significant thermal gradients. For the descent cases, a pressure load of 6.89 KPa (1 psi) ultimate with and without the thermal gradient of 716°K/389°K (830°F/240°F) was applied and was used in the stress analysis. See Figure 3 at time of 330 seconds for this maximum temperature gradient. These curves were developed from heating rates for body point 3140 (Reference 8) and a one dimensional computer model using conduction analysis. These pressure and thermal gradients are tabulated in Table 1, Design Criteria.

3.2 FINITE ELEMENT MODEL

A two-dimensional finite element model of the entire panel was constructed in order to determine the internal stresses and external deflections for the above pressure/temperature gradients. The model, shown in Figure 4, has 177 nodes. This number of nodes meshes the panel into a series of 25.4 mm by 25.4 mm (1.0 inch by 1.0 inch) plate members.

This size is considered to be sufficiently fine to accurately define stresses and deflections. The computer code selected for the analysis was NASTRAN-Cosmic, Level 17.0. The selection was based on the fact that it has industry-wide acceptance and use, and that Rohr has extensive experience with it. The titanium sandwich panel was modeled as CQUAD1 plate members.

CQUAD1 are special plate members representing sandwich structure. The clips and bayonets were modeled as rod elements. These rod elements represent spring stiffnesses for the clips and bayonets. The spring stiffnesses were determined from a full panel pull test. Nomex pads were also simulated with single point constraints (SPC). These SPCs represent the degree of freedom or the boundary condition for the finite element model. Several iterations were performed to remove unrealistic reaction loads (bearing reaction points in tension) in the model. Subsequently, the pressure and thermal gradients from Section 3.1 were input to the model. The stress levels are discussed below, and the deflection values are discussed in Section 6.7, "Thermal/Pressure Gradients on Full Size Panel."

3.3 BENDING MOMENTS AND MARGINS OF SAFETY

The stress and internal load levels from the computer model were compared with values calculated by "hand" analysis. This "hand" analysis used classical plate theory, beam theory and conservative thermal analysis techniques. Close correlation between the computer results and the "hand" analysis provided a measure of confidence in the computer model. Table 2 lists the critical bending moments and margins of safety for the various parts of the panel.

For the Ascent 1 condition, the maximum bending moments occur at the middle of the fore and aft edge of the panel. (See elements 600, 611, 700, 711 in Figure 4.) The center of the panel has slightly lower bending moments. For the Descent 1 condition, the maximum bending

moments occur near the attachment clips. (See element 102, 109, 1202, 1209 in Figure 4.) For the Descent 2 condition, the location of the maximum bending moment is the same as the Ascent 1 condition except that the magnitude is slightly reduced due to offsetting thermal loads.

It should be noted that the allowable moments for the multi-wall sandwich panel are conservative values. They are based on a thermal gradient of 811°K/422°K (1000°F/300°F) instead of 716°K/383°K (830°F/240°F).

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4/ TOOL DESIGN AND FABRICATION

4.1 TOOL DESIGN

The panel design discussed in Section 2 shows the dimple pattern to be the same as used for the outer dimpled sheet reported in Reference 4, therefore, the only additional tool required for this task was a superplastic forming tool for forming the side closures, shown in Figure 5. Since the tool life could not be predicted, and a minimum of 104 parts would be made, the tool was designed to make four individual side closures at one firing.

4.2 TOOL FABRICATION

All tool parts were machined using a Blanchard grinder to plus or minus 0.3 mm (0.010 inch) from the nominal dimensions. The -9 and -11 flute bars were machined, using a conventional milling machine. The tool was assembled using standard bolts and dowels and standard shop practice.

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5/ TEST PANEL FABRICATIONS

5.1 TEST SPECIMEN FABRICATION

All test panels except two were fabricated 17.2 by 304.2 by 304.8 mm (0.68 by 12.0 by 12.0 inches), then subdivided to make the appropriate size test specimens. Two panels were fabricated, having clips, tongues and side closures per the drawing, shown in Figure 1, for pressure and thermal tests.

The dimpled sheets and side closures were superplastically formed, using the same process parameters reported in References 1 and 2. The skins and septum sheets were square sheared, then process cleaned per Rohr process specifications. The dimpled sheets were plated on each node, using a Rohr proprietary process. The plating thickness was verified by the installation of dummy nodes on each side of the dimpled sheet before plating, then removing after plating, and making a photomicrograph of each dummy node. The side closures were also plated 2.5 mm (0.10 inch) wide around the periphery on one side of each closure.

After plating and process cleaning, all detail parts were assembled for Liquid Interface Diffusion (LID) bonding, using the Rohr proprietary process. The parts were held together for LID bonding by resistance spot tack welding at each of the four corners. For the panels having side closures, clips and tongues, the side closures, clips and/or tongues were

resistance spot tack welded to the skins prior to layup for LID bonding. Figure 6 shows a typical assembly of parts before resistance spot tack welding. Figure 7 shows the side closures, clips and tongues resistance spot tack welded together, and the dimpled and septum sheets resistance tack welded together. Figure 8 shows the final assembly ready for LID bonding. Figure 9 shows panel after LID bonding. The hole in the corner of the panel shown in Figure 9 was caused by improper handling. It was later repaired by LID bonding a 0.01 x 12.7 x 12.7 mm (0.004 x 0.50 x 0.50 inch) Ti-6Al-2Sn-4Zr-2Mo patch over the hole. Experience will reduce the frequency of this occurrence however, the repair is relatively inexpensive and easy to make.

6/ TEST PROGRAM AND RESULTS

6.1 GENERAL

The purpose of the test program was three-fold; to provide basic mechanical properties of the LID-bonded titanium 6Al-2Sn-4Zr-2Mo multiwall sandwich, to verify the design of the titanium fastener insert, and to verify the structural and thermal performance of the panel design and manufacturing process. The basic mechanical property testing was performed on coupon-size specimens. Sub-element tests were performed on selected specimens. The structural and thermal performance verification was conducted on a full-size panel. An outline of the test program with the number of specimens involved is given in Table 3.

For the coupon and sub-element testing, the Ti-6Al-2Sn-4Zr-2Mo multiwall panels were fabricated and were visually inspected prior to testing. Specimen locations were marked on the panels. Photographs were taken of the panels for a permanent record of specimen location. Specimens were identified by a number/letter combination which related it to the panel from which it came and to the type of test that was performed on it.

The full-size panel tests closely simulated the pressure loading and temperature requirements required for Space Shuttle body point 3140. Therefore, the test results are provided as conclusive proof that the panel is able to withstand a realistic pressure load and temperature environment.

The test results quantify the strength properties of the material and verify that the panel meets all of the design requirements. The remainder of this section provides details of all the testing. These details include a description of test specimen configuration, test apparatus and procedures, and test results.

6.2 FACE SHEET TENSION TEST

These tests were conducted to determine the basic mechanical properties of duplex annealed titanium 6Al-2Sn-4Zr-2Mo foil material after being subjected to various conditions. These conditions included:

a. Processed/LID (Liquid Interface Diffusion) bonded to a dimpled sheet core.
b. Test temperatures from room temperature to 811°K (1000°F).

The following mechanical properties were determined: yield (F_{ty}) and ultimate (F_{tu}) strength, percent elongation (e%), and tension modulus of elasticity (E_t). The F_{ty} and E_t values were measured from load-deflection curves which were plotted in conjunction with an LVDT (Linear Variable Differential Transformer) on an Instron loading machine.

All specimens except the "as received" ones were cut from LID bonded Ti-6Al-2Sn-4Zr-2Mo single-layer sandwich panels. The dimpled sheet (core) was separated from the face sheets by a high-speed friction saw. The overall specimen size was 50.8 mm by 254 mm (2 inches by 10 inches) with a 25.4 mm (1 inch) wide test section with foil thickness of 0.102 mm (0.004 inch).

The test results are summarized in Tables 4 and 5. These groupings are "as received" and LID bonded to dimpled sheet (dimpled sheet subsequently removed for test).

Table 4 summarizes the testing on specimens in the "as received" condition without any pretest thermal exposure. The yield and ultimate strength and modulus of elasticity values are higher than published data (Mil-HDBK-5D) for sheet thicknesses (less than 0.046"), but the percentage elongations are somewhat lower. These increases and decreases are attributed to the rolling operations these sheets received before being sent to Rohr. The reduction in strengths from room temperature to 811°K (1000°F) is 38 percent for F_{ty}, 32 percent for F_{tu} and 26 percent for modulus of elasticity, respectively. These reductions are comparable to published data.

Table 5 summarizes the testing of specimens that were LID bonded to dimpled sheet. The F_{ty} (yield) and F_{tu} (ultimate) strengths obtained from the test results indicate that the Ti-6Al-2Sn-4Zr-2Mo is a $\alpha + \beta$ phase because it has the equivalent strengths associated with annealed mechanical properties. The reduction in strengths from room temperature to 811°F (1000°F) is 42 percent for F_{ty}, 37 percent for F_{tu} and 27 percent for modulus of elasticity, respectively. The percentage elongations are still slightly lower than published data but have increased from the "as received" values due to the LID bonding operations.

From Tables 4 and 5, the test results show that the mechanical properties of the "as received" condition are higher than of those in the LID bonded condition. The F_{ty} strengths at room and at 811°K (1000°F) temperatures for the LID bonded condition are 21 percent and 26 percent lower than the "as received" condition, respectively. For F_{tu}, the LID bonded condition is reduced 26 percent at room temperature and 31 percent at 811°K (1,000°F). The modulus of elasticity (Et) is reduced 9 percent at room temperature and 10 percent at 811°K (1000°F) from the "as received" condition. The reason for the reduction in mechanical properties for Ti-6Al-2Sn-4Zr-2Mo in the LID bonded condition is because the LID bonding operation has an annealing effect on the material properties.

6.3 CREEP TEST

The test was conducted to determine the creep-rupture of Ti-6Al-2Sn-4Zr-2Mo foil material after having been through the LID process. The creep-rupture test provided a measure of the ultimate load-carrying ability of this material as a function of time and temperature. The specimens were obtained from a panel which had 0.102 mm (0.004 inch) gage foil LID bonded to a dimpled core sheet. After the dimpled core sheet was cut away from the foil, the foil was cut into tensile specimens which measured 31.75 mm by 254 mm (1-1/4 inches by 10 inches) with a 12.7 mm (1/2 inch) wide test section. The specimens were dead-weight loaded, and a portable wrap-around furnace supplied the required temperature. The specimen's elongation and creep-time were measured using a Speedomax recorder and a LVDT. There was a total of ten specimens which were tested at elevated temperature creep. The results of the test are plotted as stress at rupture versus P, where P is the Larson-Miller parameter. The Larson-Miller parameter is a function of time and temperature at rupture. These results are shown on Figure 10.

6.4 FLATWISE TENSION

The purpose of this test was to determine the LID bond strength of attachment nodes subjected to room temperature, 589°K (600°F) and 811°K (1000°F) test temperatures. In addition, the effects of a pretest environmental exposure of 25 hours at 811°K (1000°F) in an air furnace were also investigated. The test specimens were approximately 76.2 mm by 76.2 mm (3 inches by 3 inches) and consisted of a full depth sandwich (4 layers). The specimens for testing at room temperature were bonded to steel loading blocks with FM-1000 adhesive. The other specimens were brazed to the steel loading blocks with Lithobraz BT braze alloy for 10 minutes at 1066°K (1460°F). The blocks with the specimens attached were then loaded into the test fixture as shown in Figure 11. This fixture has swivel joints at both ends to account for loading misalignments. This fixture is then located in the Instron test machine.

The pretest thermal environment exposure was performed on some flatwise tension specimens to determine the degradation of the LID bond properties over the life of a panel. It has been estimated that these panels would be exposed to 811°K (1000°F) environment for approximately 300 seconds every flight, or approximately 8 hours for 100 flights. A conservative upper limit of 25 hours was used. The atmosphere used for this exposure was conservatively sea level air.

The flatwise tension test results are summarized in Table 6. The average failure stress at room temperature for unexposed specimens is 193 KPa (28 psi). This is an improvement of 34 percent over the original node attachment design (Task I). The improvement was due to the increase of the node attachment area. The node attachment area had been increased from 1.82 square mm (0.00283 inch sq.) to 2.85 square mm (0.00442 inch sq.). All of the test specimens experienced node failure. Node failure is defined when the core (dimpled sheet) material has had tension failure leaving node tip interface material on the face sheet or septum.

The room temperature tests, on specimens which had a pretest exposure, showed an approximate 50% reduction in strength. However, it should be noted that this test is conservative in the length of pretest exposure and also in the sea level atmospheric environment since most entry heating occurs at a high altitude.

The test results of the pre-environmental exposure (25 hours at 811°K or 1000°F in an air furnace) specimens that were tested at elevated temperature show an increase in strength over the room temperature test results. It has been theorized that the higher FWT strength values at high test temperature can be explained as follows: as the test temperature increases, the titanium material becomes more ductile and the node attachment joints become more flexible. This tends to redistribute the load more uniformly into all the nodes and thereby provide higher FWT strength. This resulting strength increase is of such magnitude that it also masks the deleterious effects of the pre-environment exposure.

6.5 BEAM FLEXURE

The four point beam flexure test was conducted to determine the bending strength and stiffness of the 76 mm by 305 mm (3 inches by 12 inches) full depth sandwich specimens. The test specimens were tested at room temperature and with a thermal gradient across the specimen in the set-up shown in Figure 12.

The hot side of the specimen had a 0.102 mm (0.004 inch) Ti-6Al-2Sn-4Zr-2Mo face sheet thickness. It was heated by quartz lamps while the other side was cooled by shop air. The heat output of the lamps was regulated by altering the input current, and by shop air flow that was metered by a valve. Four Ti-6Al-4V pads 12.7 mm by 1.27 mm thick (1/2 inch wide by 0.050 inch thick) were used to distribute the applied and reaction loads into the specimens. All of the specimens were loaded in 44.5 N to 89 N (10 to 20 pounds) increments and returned to zero load after each load increment. The loads were held for 30 seconds for each incremental load. Bending deflection readings from a dial indicator were taken at center span for each load increment. The initial parts of these curves are shown in Figure 13.

There were ten test specimens. Three specimens were tested at room temperature. Three were tested at a temperature of 589°K (600°F) on the compression side and 422°K (300°F) on the tension side. The four remaining specimens were tested at a temperature of 811°K (1000°F) on the compression side and 422°K (300°F) on the tension side. One of these four specimens was tested in a creep-bending test. All of the elevated temperature specimens were brought to temperature before the load was applied.

The seven specimens that had thermal gradients through the thickness had thermocouple instrumentation. Each of these specimens had nine thermocouples installed, six on the hot side and three on the cool side.

One of the six thermocouples on the hot side of the specimen was used to control the heat intensity of the quartz lamps. The specimen that was tested in creep-bending had a moment load of 9.7 in-lbs/in applied, and it was left to creep for one hour. During the one-hour creep time, the deflection readings were taken at the center span of the specimen.

The results are shown in Table 7. The temperature range given in the table is the temperature variations along the length of the test specimens. The failure mode on seven specimens was local shear instability at the inner supports. Two specimens that were tested at room temperature had disbond and node failures respectively on the 0.102 mm (.004 inch) face sheet. The disbond failure mode occurred only after very severe buckling waves took place in the face sheet. The deflection readings indicated that some slight permanent set on all specimens occurred.

From the test results shown in Figure 13, the effective bending stiffness (EI) values were determined and tabulated in Table 8. A load value and a corresponding deflection value were taken from the Figure 13 curves and substituted into the equation that defines the bending deflection at the center of this beam. The equation, derived by energy methods, is $\Delta = \frac{3Pal^2}{48EI}$. (The symbols are explained in Figure 13.) Also presented in Table 8, for comparison purposes, are the analytically calculated EI values for this structure. These calculated values assumed that there was a linear temperature distribution and that the dimpled core did not contribute to the moment of inertia. The deletion of the contribution of the dimpled core is probably the reason that test values are 24-27% higher than the calculated values.

In Figure 13, curve B shows an initial shift in the deflection reading. This was due to improper zeroing of the dial indicator. As for the creep-bending test, the permanent set value was not available because the dial indicator reading moved to a higher deflection reading after

unloading of the specimens. This is attributable to the thermal deflections since the dial indicator did come back to a zero reading after the quartz lamps were turned off. However, visual inspection of the test specimen did not reveal any indication of permanent deformation.

6.6 THROUGH PANEL FASTENER

This test was conducted to determine the minumum load needed to pull the fastener and insert through the test panel. There were four through panel fastener test specimens, 102 mm by 152 mm (4 inches by 6 inches). These test specimens were fabricated per Rohr Drawing No. 195-260. The test setup and the specimens are shown in Figure 14. As shown, the specimen was supported by a plate with a cylindrical cutout 69.9 mm (2-3/4 inches) diameter. Three dial indicators were used to measure the deflections on the specimen doubler, the insert and the face sheet near the insert. A "pull-through" load was applied in 22.2 N (5 pounds) increments and unloaded at each incremental load until about 445 N (100 pounds) and then 44.5 N (10 pounds) increments to failure.

The ultimate load was determined when the test specimen no longer held the applied load. The limit load was determined by plotting the load-deflection curve of the insert. The limit point was obtained when the slope of the load-deflection curve decreased.

The test results are shown in Table 9. The results of the test show minimum values of 245 N (55 pounds) for limit load and 636 N (143 pounds) for ultimate load. These loads are large when compared to the design requirements which are 107 N (24 pounds) for limit and 160 N (36 pounds) for ultimate loads. There were two failure modes in this test. They were outer face sheet tear-out with internal panel failure, as shown in Figure 15, and shear of fastener insert flange as shown in Figure 16. Photomicrographs of the fastener insert flange show that shear failure

was due to machining the insert flange too thin as shown in Figure 17. This explains the lower ultimate test loads found for these specimens. The actual production parts will require tighter tolerances on the machining of this insert flange.

6.7 THERMAL PRESSURE GRADIENTS ON FULL SIZE PANEL

6.7.1 GENERAL -- In order to verify the structural integrity of a total panel assembly, a series of thermal and pressure gradient tests was conducted. A panel assembly, which was fabricated to Rohr Engineering Drawing 195-258, Revision A, was clipped into a test fixture in a manner which accurately simulated a shuttle installation. The test panel, instrumented with thermocouples is shown in Figure 18.

6.7.2 TEST FIXTURE AND INSTRUMENTATION -- The test fixture (Rohr Drawing 501-560, Revision A, is shown schematically in Figure 19 and by photographs in Figures 20 through 24. In the schematic, starting at the bottom, there are dial indicators with ceramic dowels which penetrate through the quartz lamps. The quartz lamp bank array is shown in Figure 21. The ceramic dowels, shown protruding through the lamps, must penetrate a water chamber which circulates water to cool and protect the aluminum support plate. Surrounding the lamp bank is a rectangular, gold-plated reflecting shield which keeps the heat in and on the panel (Figure 20).

Above this lamp assembly, a completely independent and separate assembly is suspended. This assembly contains the test panel, mounting clips, seals and a pressure chamber to load the panel. The test panel has its exterior surface exposed directly to the lamp array. The panel is clipped into the base of the pressure chamber. Figure 22 shows this chamber in an inverted position and without the cover plate. Note that the clips and bayonet fittings for the normal mating structure are included.

Also shown in this figure (and in Figure 19) are two different seals. The design and function of these silicone seals are very important. The seal, on the outer perimeter, simulates the Nomex pad that would be installed on the shuttle vehicle. This pad is compressed during panel installation and provides a tight fit for the panel. It also reacts crushing pressure loads that push the panel against the vehicle. The test seal is purposely not bonded to the panel so that it will not inadvertently react blowoff pressure loads that pull the panel away from the shuttle. The inner seal is referred to as the flap seal, and it provides the seal to the pressure chamber. As such, it must be bonded to the panel, but also must not react any blowoff loads. This is possible because of its design. The silicone seal is L-shaped and has very low bending stiffness. Consequently, the seal is incapable of reacting any load. Therefore, all loads must go through the clips as required. Figures 23 and 24 show views of this seal as it attaches to the bottom of the panel. Although Figure 24 shows an Inconel panel from Reference 5, the setup is similar for the titanium panel. The final part of the fixture is a cover plate which is bolted on. A vacuum pump provides crush pressure, and an external air supply provides blowoff pressure. Both are monitored by a pressure gauge.

Figure 20 shows, on the far left, a Thermac Controller (Research, Inc.) which regulates power to the quartz lamps. To the right of this is a Data Logger (Fluke) which records the temperatures from the thermocouples. All thermocouples were chromel/alumel attached by spot welding to the panel.

6.7.3 TEST PROGRAM AND RESULTS -- The testing was performed as a series of five conditions as outlined in Figure 25. The intent of the program was to cover as many possible design conditions as practical and to do so in a conservative manner. The design pressure is 1 psi ultimate and the design surface temperature is 811°K (1000°F). In this test program, the limit crush pressure was first applied at room temperature

and then with a conservative thermal gradient of 811°K/422°K (1000°F/300°F), respectively. Subsequently, the panel was subjected to the limit burst pressure at room temperature and then with a thermal gradient of 811°K/422°K (1000°F/300°F). After successfully passing these test conditions, the loading with the thermal gradient was increased to determine margin of safety. At 20.7 KPa (3.00 psi) an air leak took place in the pressure chamber and the testing was stopped to protect the test fixture. Post-test inspection revealed no failure in the panel. The heat-up rates on the test panel were controlled and were those calculated for a re-entry condition. These temperatures were monitored during heat-up and during load application. Figure 26 shows the location of the eight thermocouples. This figure also tabulates the temperatures for various pressure loads. The temperature table shows that thermocouples Number 1, 2, 6, 7 and 8 are very consistent with each other on the hot side of the panel during testing. The temperatures in the remaining three thermocouples decreased in value as the pressure load increased. This behavior was due to the air which supplied the pressure load and cooled the thermocouples on the cool side of the panel.

Figure 27 plots the deflections at the center of the panel versus applied pressure loads. For the critical design conditions of 6.9 KPa (1.0 psi), burst pressure plus 811°K/422°K (1000°F/300°F) temperature gradient, the deflection at the center of the panel is 5.08 mm (0.20 inch), 3.63 mm (0.143 inch) due to thermal and 1.45 mm (0.057 inch) due to pressure or a total of 5.08 mm (0.20 inch). Also shown in this figure is a nonlinear behavior of the panel under a combined crush pressure and thermal loading. In order to relate this to panel bow, Figure 28 was plotted. This plot shows deflection values at all four corners of the panel, the middle of a side, and also the center of the panel for the critical design condition. The plotted deflections are those due to pressure only, and the thermal deflections are presented in table form. In order to calculate maximum panel bow, the corner with the smallest deflection has its value subtracted from the panel center deflection. For the

6.9 KPa (1.0 psi) 811°K/422°K (1000°F/300°F) condition, Number 1 corner has the smallest deflection. This value is 0.813 mm (0.032 inch), 0.483 mm (0.019 inch) due to thermal and 0.330 mm (0.013 inch) due to pressure.

Therefore, the maximum panel bow for the ultimate design condition is 5.08 mm minus 0.813 mm or 4.27 mm (0.168 inch). The nonlinearity in the deflection curves above the 6.9 KPa (1.0 psi) load is attributed to bending in the clips.

Figure 29 presents a comparison of deflections obtained from the test results versus those calculated using the NASTRAN finite element model as described in Section 3.2. Note that the crush pressure condition was conducted at a maximum pressure of 4.6 KPa (0.67 psi). So for direct comparison purposes, the burst pressure deflections are also tabulated at this pressure. The deflections calculated for a 4.6 KPa (0.67 psi) crush pressure case (loading condition II) do not agree with the measured deflection values. The reason for this disagreement in deflections is that in the modeling technique, the finite element model was supported with NASTRAN SPC's (Single Point Constraint) as a boundary support. The SPC boundary is supposed to represent the Nomex pad boundary, but the SPC constraint is a rigid boundary constraint, thus the finite element model shows lower deflections than the tested values.

The deflections calculated for 4.6 KPa (0.67 psi) burst pressure case (loading condition I) are in fair agreement with the test results, for example, 0.940 mm (0.037 inch) deflection analytical versus 0.711 mm (0.028 inch) test at the center of the panel. However, the deflection value for analytical results at the center of the edge of the panel does not agree with the measured result, because the finite element model does not include the corrugated side walls. These corrugated side walls will increase the bending stiffness of the panel, especially along the edges. The existing finite element model used a two-dimensional element to model the TPS panel in its entirety, therefore, modelling the corrugated side

walls was not possible. As for the thermal deformation at the center of the panel, the deflection results agree very well except at the outer edge of the panel. At the center edge of the panel the deflection value is higher for the analytical than the test result. This is again due to the missing corrugated side walls in the finite element model as mentioned above.

In addition to the limitations in modelling techniques mentioned above, some minor shortcomings need mentioning: (1) modulus of elasticity and thermal coefficient of expansion values were not adjusted for temperature, (2) linear temperature gradient applied across the layer is not precisely correct, and (3) the solution to this problem requires a non-linear computer approach, whereas a linear one was used.

6.8 THERMAL CONDUCTIVITY/EMITTANCE

It was not expected that any significant changes in conductivity from the Reference 1 values would occur. But because the side wall enclosures were changed from 0.524 Rad. (30 degrees) to 1.571 Rad. (90 degrees) and the node's spot diameter was increased by 0.38 mm (0.015 inch) from 1.524 mm (0.060 inch) to 1.905 mm (0.075 inch), it was decided to repeat the conductivity tests.

Thermal conductivity tests were performed on a panel having approximate dimensions of 17.3 by 305 by 305 mm (0.68 inch by 12 inches by 12 inches). The tests were run on the same modified guarded hot plate apparatus used for conductivity testing in References 1 and 2.

Test results are shown in Figure 30. For comparison, results from the original configuration are also included in the graph. It is noted that most values are unchanged from those reported in Reference 1. There is some difference at the highest temperature, but this is attributed to the long run times at high temperatures required because of unfamiliarity with the test equipment at the time the panels having 30-degree side walls were tested.

After these tests were completed, an additional panel, deliberately vacuum sealed, became available for tests. It was expected that a significant k reduction would occur because the vacuum removes air k contribution from the panel's overall k value. The panel was vacuum checked before and after the k tests by immersing it in 150°F water. No air bubbles were detected either before or after testing. Test results of k values are given in Figure 30. They are disappointing since the values essentially are the same as the no vacuum panel. Evidently, only a partial vacuum was retained in the panel.

Because the design was changed to include Ti-6Al-2Sn-4Zr-2Mo, it was necessary to check this material for emittance. The test results shown in Figure 31 are very close to the Ti-6Al-4V reported in References 1 and 2.

7/ FABRICATION OF PANEL ARRAYS

7.1 FABRICATING DETAIL PARTS

The panel side closures were superplastically formed at 1200°K (1700°F) in a vacuum furnace evacuated to 5 x 10^{-5} Torr. After the tool and part temperature reached 1200°K (1700°F), the tool was pressurized to 138 Kpa (20 psi) using argon gas. The pressure was maintained at that level for ninety minutes. After forming, the parts were trimmed net using hand shears. The dimpled sheets were superplastically formed using a static pressure load of 4.8 KPa (0.7 psi). The same time and temperature was used as for forming the side closures so that furnace loads could be intermixed for economic reasons.

The skins and septum sheets were square sheared to net dimensions. The clip and tongues were hot formed, using a conventional hot forming press. The through panel fasteners were machined net per drawing. All fabrication was performed in accordance with Rohr planning where the operator and the inspector had to verify that each step of the fabrication procedure had been properly performed by affixing identification stamps at each operation on the planning. Figure 32 shows typical planning used in the fabrication of detail parts.

7.2 FABRICATING THE PANELS

The prefabricated detail parts were processed in lots of six. After plating and process cleaning, all detail parts where assembled for LID bonding, using the Rohr proprietary process. The parts were held together for LID bonding by resistance spot tack welding at each of the four corners. For the panels having side closures, clips and tongues, the side closures, clips and/or tongues were resistance spot tack welded to the skins prior to layup for LID bonding. Figure 33 shows LID bonded panels being removed from furnace. After LID bonding, the panels were checked visually, dimensionally and with ultrasonic pulse echo of each face sheet to dimpled sheet bond joint.

The visual inspection showed that some panels had waviness of the face sheets, some had been damaged from handling, some also had very small openings at the intersection of the side closures at the corner; see Figures 35 through 40. Previous tests showed that waviness of the face sheets was not a structural problem. The damaged areas were repaired by LID bonding a small patch over the affected area. Experience in handling and the possible use of protective aid during the fabrication process is expected to eliminate this type of damage.

An internal pressure check to 6.895 KPa (1 psi) was performed, using a Meriam Manometer with Meriam 295 Red Fluid (2.95 specific gravity) shown in Figure 34. While the panel was being pressurized, it was observed for noise and bulges. One previously rejected panel with known dimpled sheet to face sheet bond voids was tested to failure as a standard. Where the known voids were, a bulge would occur; when additional joints failed, a loud noise was heard.

Overall evaluation of these panels show that bond quality is much better than was achieved on the panels having thirty-degree sloped sides reported in Reference 2 and that large quantities could be economically produced by this method.

After all deliverable panels had been completed and shipped, Rohr became aware of an Automated Ultrasonic Scanning facility which has the potential for finding disbonds at various depths in sandwich structures. This automated facility uses ultrasonic through transmission or pulse echo in conjunction with a computer to look at various depths of a sandwich structure. The computer looks at the sound level going in and coming out and can divide it into sixteen layers. These layers can be viewed separately on a video screen in 16 shades of gray or a printout can be obtained from the attached printer.

One vacuum tight panel, one vented panel that had been rejected for furnace related problems, and one test specimen with known voids were evaluated using the Automated Ultrasonic Scanner. Through transmission was used to evaluate the vacuum tight panel and the test specimen. Figures 41 and 42 shows the through transmission printouts. Only the node bonds of alternating layers can be seen. The transducers were manipulated and indications are that with some development through transmission could be used to determine disbonds in vacuum tight panels. Pulse echo transmission was tried without success.

The vented panel was filled with water and evaluated using through transmission. Figures 43, 44 and 45 show typical printouts from the Automated Ultrasonic Scanner. All node bond areas can be seen. The contrast changes as the computer looks at the various sound levels which correspond to different layers as shown by Hi and Low DB on the printouts.

Only a limited time was spent on these evaluations. Some development is required to match the transducer to the part, and some test specimens must be fabricated for use as standards for setting up the Automated Ultrasonic Scanner. Indications are that this equipment is capable of detecting node disbonds in Titanium Multiwall Thermal Protection System Panels.

7.3 FABRICATING THE ARRAYS

Two panels were installed on an aluminum plate 3.8 mm (0.15 inch) by 406.4 mm (16.0 inches) by 762 mm (30.0 inches) which approximates the shuttle fuselage mass at body point 3140. This array was shipped to NASA Johnson Space Center for tests in the Radiant Heat Facility.

An array of twenty panels was designed, shown in Figure 46, and fabricated for test in the NASA Langley Research Center High Temperature Structures Tunnel. The twenty panels were mounted on the 3.8 mm (0.15 inch) by 1077.7 mm (42.430 inches) by 1522.2 mm (59.930 inches) aluminum plate shown in Figure 47, using both the through panel fasteners and the clip and tongue fasteners. The through panel fastener concept was developed for the purpose of removing and replacing panels locally, which cannot be done when the clips and tongues are used. The through panel fastener has another advantage: panels can be installed without sliding the panel over the Nomex felt. Installation of panels having clips and tongues requires the panel edge to be slid across the Nomex felt to engage the tongue into the clip on the aluminum plate and the clip on the preceding panel. It is more difficult to install panels having clips and tongues. The Nomex felt is necessary to prevent panel vibration and air flow under the panel.

The array was designed to fit an existing test apparatus. Therefore, some panels were smaller than the standard size 17.2 mm (0.68 inch) by 304.8 mm (12.0 inches) by 304.8 mm (12.0 inches) panel. This did not present a fabrication or installation problem.

The Nomex felt was installed with room temperature curing silicone rubber. The Nomex felt was also sealed around the edges with silicone rubber to prevent gas from flowing through the felt and under the panels.

8/ CONCLUSIONS

The 1.571 Rad (90 degrees) side closure configuration panels are easier to tool aid for LID bonding, resulting in better bond quality. The 1.9 mm (0.075 inch) diameter nodes improved the sandwich strength. The redesigned panel meets the mechanical and thermal requirement for shuttle body point 3140. The panels were produced in a production environment, including quality assurance. Large quantities could be produced using existing technologies and facilities.

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9/ REFERENCES

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Table 1. Design Criteria - Body Point 3140

Load Condition	Δ Pressure Ultimate KPa	(psi)	Δ Temperature °K	(°F)	T_{max} °K	(T_{max} °F)
Ascent 1	+6.89	(+1.00)	0	(0)	Room Temp.	
Descent 1	0	(0)	583	(590)	716	(830)
Descent 2	+6.89	(+1.0)	583	(590)	716	(830)

Table 2. Bending Moments and Margins of Safety

Component	Load Condition	Ultimate Calculated Moment N-m/m (in-lb/in)	Ultimate Allowable Moment N-m/m (in-lb/in)	Failure Mode	Margin of Safety
Basic Sandwich	Ascent 1	55.6 (12.5)	248 (55.6)(3)	Intracell Buckling	High
Basic Sandwich	Descent 1	19.6 (4.4)(1)	191 (42.9)(3,4)	Intracell Buckling	High
Basic Sandwich	Descent 2	54.7 (12.3)(2)	191 (42.9)(3,4)	Intracell Buckling	High
Attachment Clips (Local bending)	Descent 2	35.3 (7.93)	37.0 (8.33)(5)	Bending	+.05

(1) Moment due to 716°K/383°K (830°F/240°F) thermal gradient.

(2) Combined ascent and descent load conditions (i.e., pressure and thermal gradient).

(3) Allowable moments were obtained from room temperature beam flexure test results.

(4) Allowable moment was determined from 811°K/422°K (1000°F/300°F) thermal gradient beam flexure test results.

(5) Used a temperature reduction factor for 422°K (300°F) for ultimate stress allowable.

Table 3. Structural Test Summary

Test Type	Pre-Test Elevated Temperature Exposure	Elevated Test Temperature	Number of Specimens
Face Sheet Tension[1]	No	Yes	18
Face Sheet Creep[2]	No	Yes	10
Flatwise Tension[3]	Yes	Yes	12
Beam Flexure[4]	No	Yes	10
Through Panel Fasteners[3]	No	No	4
Full Panel Pressure/Temperature Gradient	No	Yes	1

1 Test specimens are Ti-6-2-4-2 foil material, both as received and after LID bonded.

2 Test specimens are Ti-6-2-4-2 foil material as received.

3 Full depth multiwall sandwich.

4 Included one creep in bending specimen, full depth.

Table 4. Ti 6-2-4-2 Face Sheet Tension Sheet - As Received
No Pretest Environmental Exposure

Test Temperature K° (°F)	F_{ty} MPa (ksi)	F_{tu} MPa (ksi)	e %	E_t GPa (ksi x 10^3)
RT	1122 (162.8)	1302 (188.9)	5.0	118 (17.1)
589 (600)	926 (134.3)	1038 (150.5)	3.0	114 (16.6)
811 (1000)	686 (101.0)	881 (127.8)	4.1	87.6 (12.7)

NOTE 1: All specimens are 0.102 mm (0.004 inch) thick.

NOTE 2: All values are an average of three test points.

Table 5. Ti 6-2-4-2 Face Sheet Tension Sheet - LID Bonded to Dimpled Sheet (Dimpled Sheet Removed for Test)

Test Temperature K° (°F)	F_{ty} MPa (ksi)	F_{tu} MPa (ksi)	e %	E_t GPa (ksi x 10^3)
RT	891 (129.2)	969 (140.5)	6.0	108 (15.6)
589 (600)	582 (84.4)	672 (97.4)	5.0	93.1 (13.5)
811 (1000)	517 (75.0)	881 (88.8)	6.7	78.6 (11.4)

NOTE 1: All specimens are 0.102 mm (0.004 inch) thick.

NOTE 2: All values are an average of three test points.

Table 6. Flatwise Tension Tests Full Depth Sandwich

ROOM TEMPERATURE	SPECIMEN ID (3)	FAILURE LOAD N, (LBS)	FAILURE STRESS KPa, (PSI)	FAILURE MODE
Room Temperature (No pretest exposure)	A-FWT-1(1)	1250 (281)	215 (31.2)	Node failure
	A-FWT-2(1)	1023 (230)	176 (25.5)	Node failure
	A-FWT-3(1)	1094 (246)	188 (27.3)	Node failure
	A-FWT-4(1)	863 (194)	148 (21.5)	Node failure
	A-FWT-5(1)	1237 (278)	213 (30.9)	Node failure
	A-FWT-6(1)	1277 (287)	219 (31.8)	Node failure
	Average	1124 (252.7)	193 (28.0)	
Room Temperature (25 hrs. of 811°K pre-test exposure)	B-FWT-1	440 (99)	76 (11.0)	Node failure
	B-FWT-2	560 (126)	96 (13.9)	Node failure
	B-FWT-3	311 (70)	54 (7.8)	Node failure
	B-FWT-4	569 (128)	98 (14.2)	Node failure
	B-FWT-5	578 (130)	99 (14.4)	Node failure
	Average	494 (111)	85 (12.3)	
589°K, (600°F) (25 hrs. of 811°K pretest exposure)	(2) A-FWT-7	814 (183)	(4) 140 (20.3)	(4) 75% Node & 25% LID
	A-FWT-8(2)	1797 (404)	309 (44.8)	Node failure
	A-FWT-9(2)	1552 (349)	268 (38.8)	Node failure
	Average	1388 (312)	239 (34.6)	
811°K, (1000°F) (25 hours of 811°K pretest exposure)	(2) A-FWT-10	351 (79)	(4) 60 (8.8)	(4) 60% Node & 40% LID
	A-FWT-11(2)	2135 (480)	366 (53.1)	Node failure
	A-FWT-12(2)	1664 (374)	286 (41.5)	Node Failure
	Average	1383 (311)	238 (34.5)	

NOTE: All specimens have been in LID bond cycle.
(1) Adhesively bond loading blocks.
(2) Exposure 25 hours at 1000°F in air furnace and braze loading block.
(3) First letter designates the panel from which the specimens were cut. The FWT stands for flatwise tension.
(4) Lower test value is dependent on failure mode.

Table 7. Beam Flexure Tests -- 3" x 12" Test Specimen

SPECIMEN I.D. (2)	TEST TEMPERATURE RANGE		TOTAL FAILURE LOAD		FAILURE MODE
	TENSION SIDE °K (°F)	COMPRESSION SIDE °K (°F)	N/m	(LBS/IN)	
A-BF-1	Room Temperature	Room Temperature	9807	(56.0)	Node failure at inner support.
A-BF-2	Room Temperature	Room Temperature	9930	(56.7)	Disbond of .102 mm (.004") face sheet at near center of specimen.
A-BF-3	Room Temperature	Room Temperature	9457	(54.0)	Local shear instability inner supports.
Average			9731	(55.6)	
B-BF-4	394-408 (250-275)	570-598 (566-617)	6707	(38.3)	Local shear instability at inner support.
B-BF-5	396-416 (253-290)	573-597 (571-615)	7408	(42.3)	Same as above
C-BF-6	394-398 (249-257)	566-593 (559-607)	7303	(41.7)	Same as above
Average			7139	(40.8)	
C-BF-7	416-436 (289-326)	800-815 (980-1008)	7180	(41.0)	Local shear instability at inner support.
C-BF-8	409-450 (277-350)	790-826 (962-1027)	8931	(51.0)	Same as above
C-BF-9	430-446 (314-344)	802-829 (984-1033)	6427	(36.7)	Same as above
Average			7513	(42.9)	
C-BF-10	399-425 (258-306)	797-820 (975-1017)	1699	(9.7)(1)	No failure

(1) This is the sustained applied load without failure (creep in bending test).

(2) First letter designates the panel from which the specimens were cut. The BF stands for beam flexure.

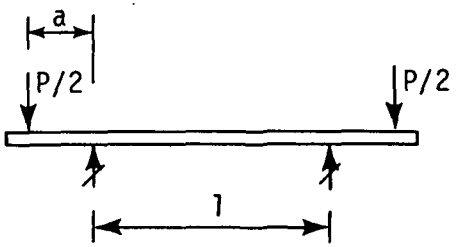
Table 8. Effective Stiffness of Beam Flexure Test

TEST TEMPERATURE GRADIENT °K (°F)	TOTAL LOAD N/m (lb/in)	AVERAGE DEFLECTION(1) mm (inch)	TESTED EI_{EFFECT} (2) $N\text{-}m^2/m$ ($lb\text{-}in^2/inch$)	CALCULATED (3) EI $N\text{-}m^2/m$ ($lb\text{-}in^2/in$)
R.T.	2335 (13.33)	.089 (.0035)	1932 (17,140)	1558 (13,820)
422-589 (300-600)	2335 (13.33)	.100 (.0039)	1720 (15,380)	1362 (12,080)
422-811 (300-1000)	2335 (13.33)	.107 (.0042)	1607 (14,280)	1290 (11,450)

(1) Readings were taken on the beam flexure test load curves shown in Figure 13.

(2) Effective EI was obtained from the four points loading deflection equation $\Delta = \frac{3Pal^2}{48EI}$.

a = distance between load point and adjacent reaction point, 0.0508 m.
l = distance between two reaction points, 0.152 m
P = the total of the two point load applications
E = modulus of elasticity
I = section moment of inertia



(3) Hand calculation used only face sheets and septum sheets for bending stiffness calculations.

Table 9. Static Pull Load Allowable - Titanium Panel Fastener

SPECIMEN I.D.	LIMIT LOAD N (LBS)	ULTIMATE LOAD N (LBS)	ULTIMATE FAILURE MODE
1	245 (55)	1379 (310)	OUTER FACE SHEET TEAR OUT AND INTERNAL PANEL FAILURE
2	400 (90)	801 (180)	SHEAR OF FASTENER INSERT FLANGE
3	356 (80)	1535 (345)	OUTER FACE SHEET TEAR OUT AND INTERNAL PANEL FAILURE
4	534 (120)	636 (143)	SHEAR OF FASTENER INSERT FLANGE
AVERAGE	383 (86)	1085 (244)	
MINIMUM	245 (55)	636 (143)	

DESIGN LIMIT LOAD = 2/3 X 1 PSI X 144 IN^2 ÷ 4 FASTENERS = 107 N (24 LBS.)

DESIGN ULTIMATE LOAD = 1 PSI X 144 IN^2 ÷ 4 FASTENERS = 160 N (36 LBS.)

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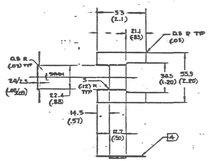
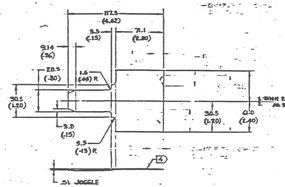
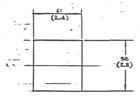


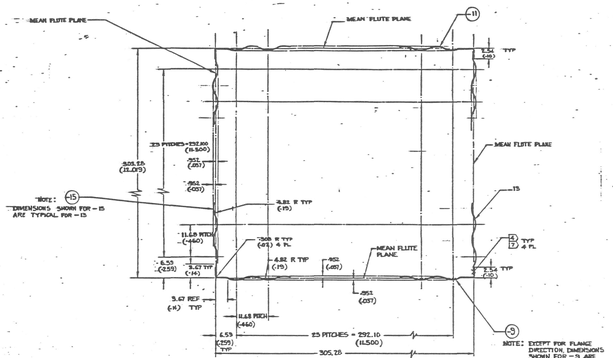
DETAIL (17)



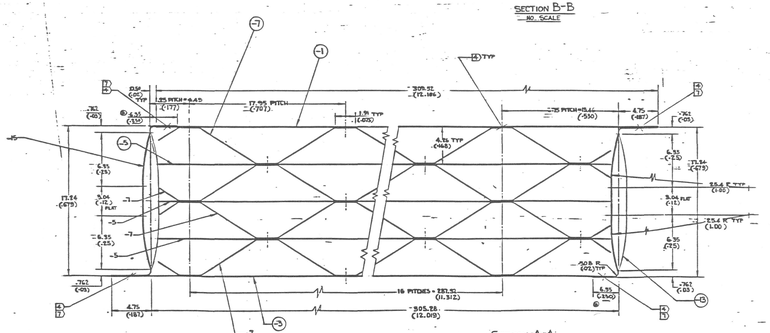
DETAIL (21)
NO SCALE



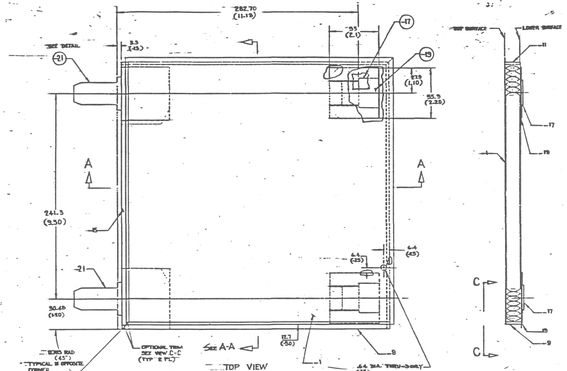
DETAIL (15)



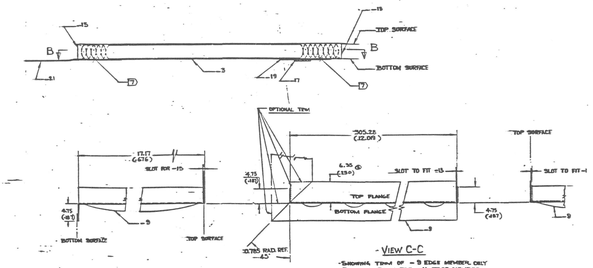
SECTION B-B
NO SCALE



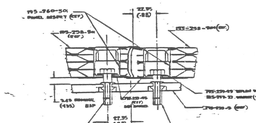
SECTION A-A
SCALE 10/1



TOP VIEW



VIEW C-C
SHOWING TYP OF ~9 EDGE MEMBERS. ONLY TYPICAL TRIM FOR ~11 EDGE MEMBER.
SCALE 4/1



SECTION N-N (TYP).
SCALE 5/1

GENERAL NOTES
UNLESS OTHERWISE SPECIFIED

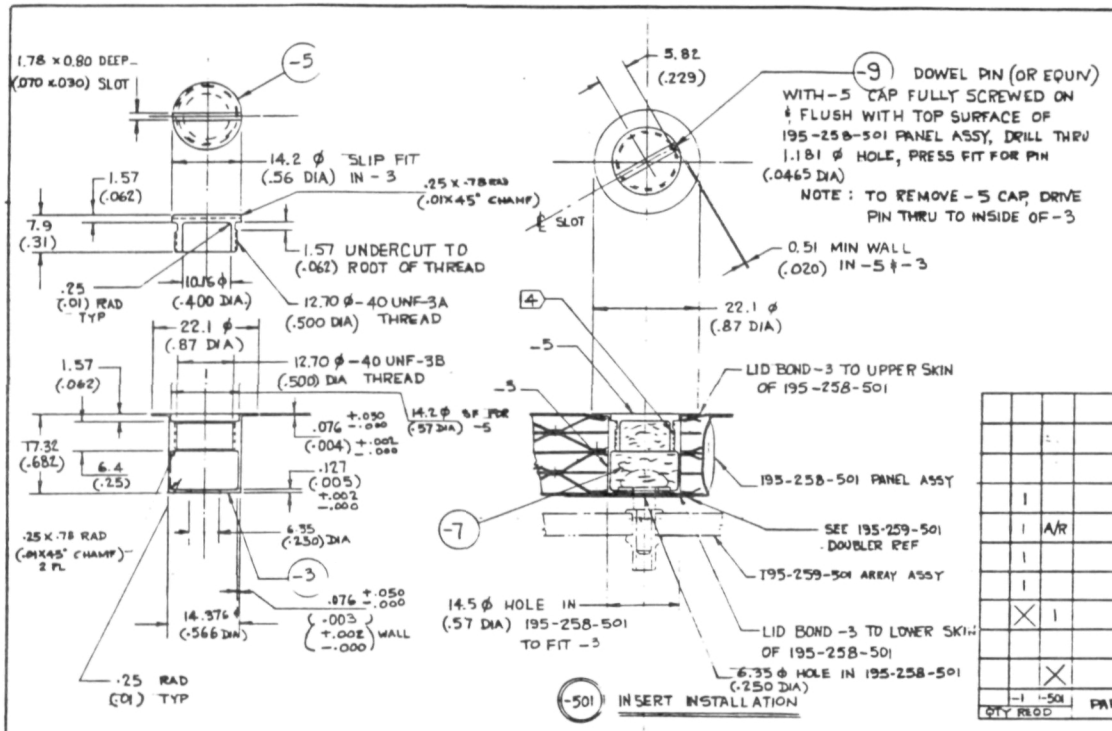
1. DIMENSIONS IN S.I. UNITS & (SUPPLEMENTARY UNITS); mm (in), rad (deg), N/m² (psi), K (°F)
2. TOLERANCES:
   LINEAR: .X = ±.2 (±.8); .XX = ±.25 (±.010); .XXX = ±.050 (±.002)
   ANGULAR: .X = ±.1; .X = ±.5; .XX = ±.01; .XX = ±.005
3. SEE 195-261 FOR TOOL TO MAKE CLOSURES, ~9, ~11, ~15, & ~15 .
4. LO PLATE THESE SURFACES PER RPS 11-30 OR PREPARATION FOR BONDING .
5. FORM TITANIUM PARTS PER RPS 11.01 .
6. DIMPLE SHEET ~7 TO BE MADE ON TOOL NO 196-234 .
7. SPOTWELD COMPONENTS IN POSITION IN PREPARATION FOR BONDING .
8. IDENTIFY ALL PARTS & ASSY'S PER RPS 15.75 BARREL STAMP LOCATION OPTIONAL .
9. IMPRESSION STAMPING NOT PERMITTED .
10. PROCESS BOND ASSY PER RPS 11.22 .
11. LO BOND IN A VACUUM ENVIRONMENT PER RPS 11.24

12. PERPENDICULAR WAVINESS ≤ 0.25 (.010) BETWEEN ADJACENT SIDES
13. TEFLON TAPE MAY BE USED AS A SUBSTITUTE .
14. 195-258-301 REPRESENTS THE BASELINE PANEL. SEE NEXT ASSY 195-258 FOR MODIFICATIONS TO PANELS NECESSARY TO FIT TO PANEL ASSEMBLY 195-253 .

ITEM	QTY	PART NO	DESCRIPTION	MATERIAL	SIZE (in)	SPEC	NT
	1	-21	TONGUE	Ti-6AL-4V	.051 × 8.64 × 5	AMS 4911	
	2	-15	DOUBLER	Ti-6AL-4V	.010 × 5.3 × 2.4		
	2	-17	CLIP	Ti-6AL-4V	.075 × 2.1 × 2.5	AMS 4911	
	1	-15	CLOSURE	2024-T3 OR Z12.2 × .025 × 0.2 × 14		MIL-T-5066	
	1	-13					
	1	-11					
	1	-9	CLOSURE		.025 × 1.1 × 14		
	14	-7	SHEET - DIMPLED		.025 × 16 × 14		(13)
	15	-5	SEPTUM -		.025 × 13 × 15		(13)
	11	-3	SKIN - LOWER		.029 × 15 × 13		(13)
	11	-1	SKIN - UPPER	2024-T3 OR Z12.2 × .03 × 13 × 15		MIL-T-9046	
	1	-301	PANEL ASSY (14)				

Figure 1. Panel Assembly – NASA T.P.S.

	INDUSTRIES, INC.
	PANEL ASSY – NASA T.P.S.
SIZE	31563
	135-258



REVISIONS				
ZONE	LTR	DESCRIPTION	DATE	(APPROVED)

GENERAL NOTES UNLESS OTHERWISE SPECIFIED

1. DIMENSIONS IN S.I. UNITS [ ] (CUSTOMARY UNITS) mm (in), rad (deg)
2. TOLERANCES: LINEAR X. = ±2 .X = ±.7 .XX = ±.25 (.X = ±.1 .XX = ±.03 .XXX = ±.010)
   ANGULAR X = ±.1 XX = ±.01 .XXX = ±.001 (X. = ±2 .X = ±.5 .XX = ±.05)
3. EQUIVALENT MATERIAL MAY BE SUBSTITUTED WITH ENGINEERING APPROVAL.
4. APPLY ANTI-SEIZE COMPOUND TO THREADED AREA PER RPS. 1382.
5. TI-6AL-2SN-4ZR-2MO MAY BE USED AS A SUBSTITUTE.

QTY REQD -1	QTY REQD -501	PART NO	DESCRIPTION	MATERIAL	SIZE (in)	SPEC	HT	
1		-9	DOWEL PIN	TI-6AL-4V	(.0465 DIA x 5/16 LG)			5
1	A/R	-7	Q-FIBER FELT	Kg/m³ (3.5 LB/FT³)				
1		-5	THREADED CAP	TI-6AL-4V	(5/8 DIA x 1/2 LG)			5
1		-3	HOUSING	TI-6AL-4V	(1.0 DIA x 1 LG)			5
X	1	-1	INSERT ASSY					
	X	-501	INSERT INSTL					

DRAWN	NESTOR	7-31-81	
CHK			
ENGR	BERNARD	8-4-81	
THERMO	EQUIVALENT	7-28-81	
MECH. APPR.			
MFG. ENG.		7-27-81	
QUAL. ENG.		8/28/81	
PLANNING NO.			

INDUSTRIES, INC.

PANEL ATTACH BOLT INSERT INSTALLATION - NASA T.P.S.

SIZE	CAGE IDENT NUMBER	DWG NO	REV
	51563	195-260	

SCALE 2/1 SHEET 1 OF 1

47/48 (blank)

Figure 2. Panel Attach Bolt Insert Installation - NASA T.P.S.

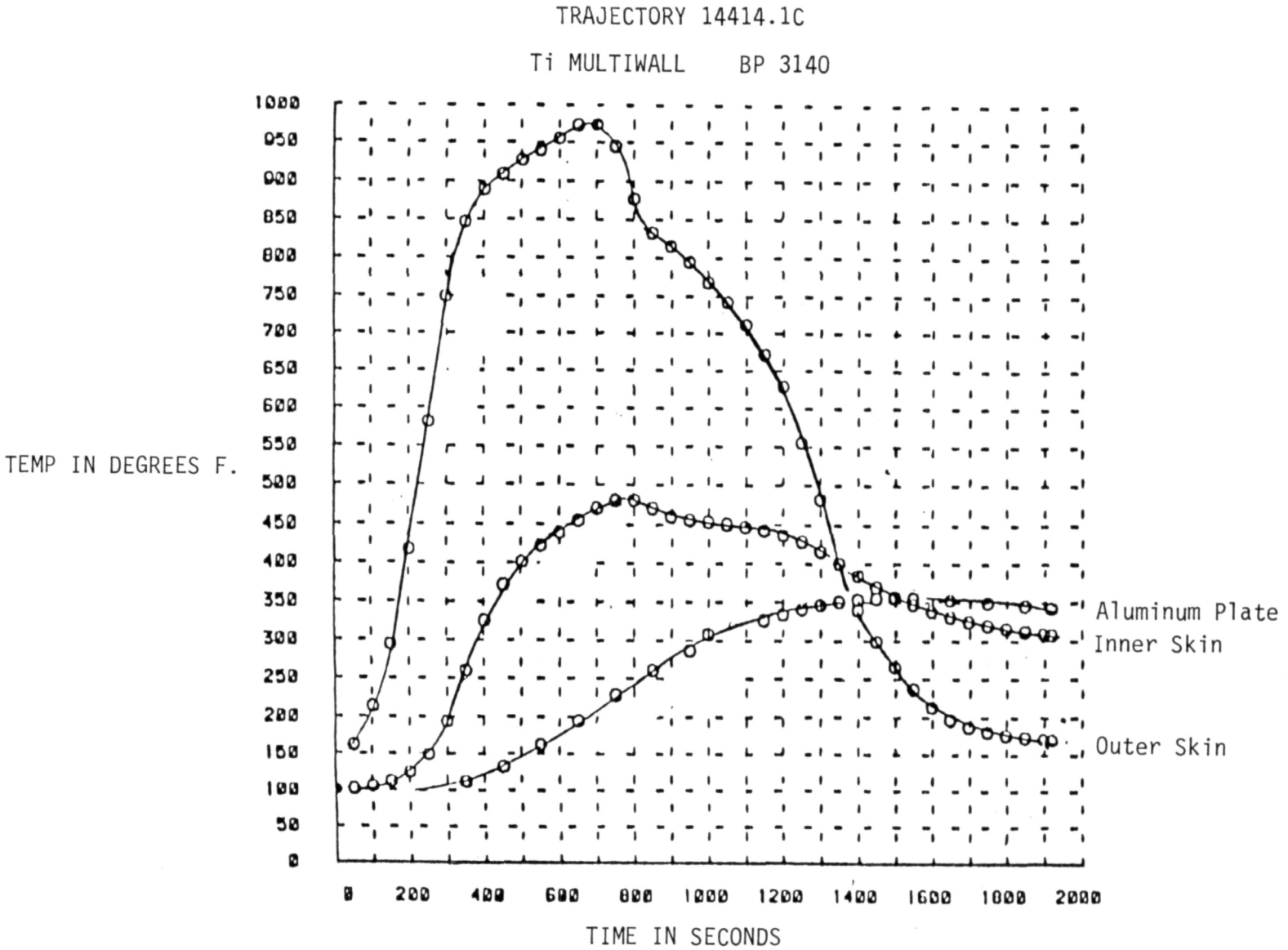
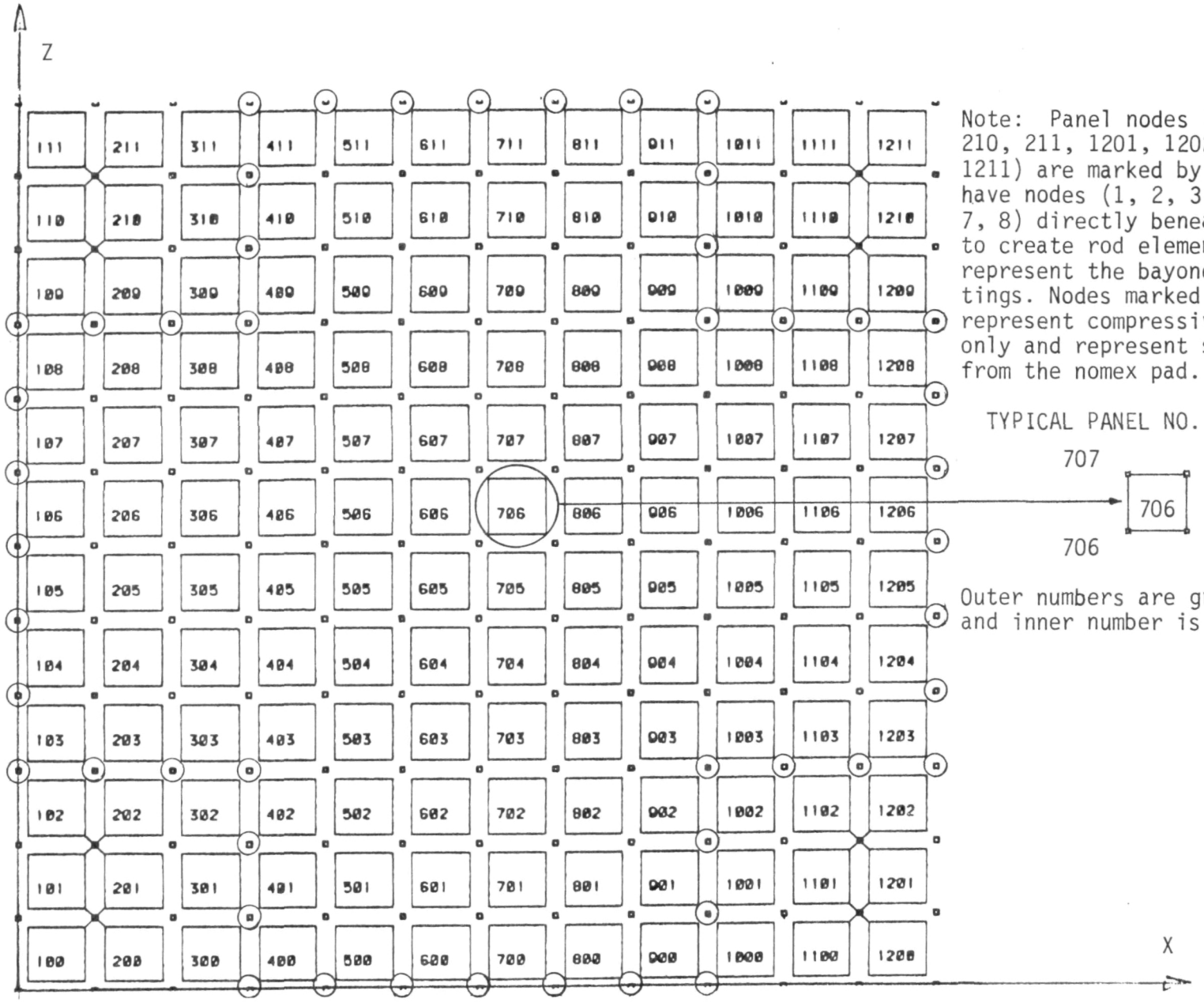


Figure 3. Heating Rates



Note: Panel nodes (201, 202, 210, 211, 1201, 1202, 1210, 1211) are marked by an X and have nodes (1, 2, 3, 4, 5, 6, 7, 8) directly beneath them to create rod elements which represent the bayonett fittings. Nodes marked by circles represent compressive supports only and represent support from the nomex pad.

TYPICAL PANEL NO. SYSTEM

Outer numbers are grid points and inner number is panel number.

Figure 4. Finite Element Model

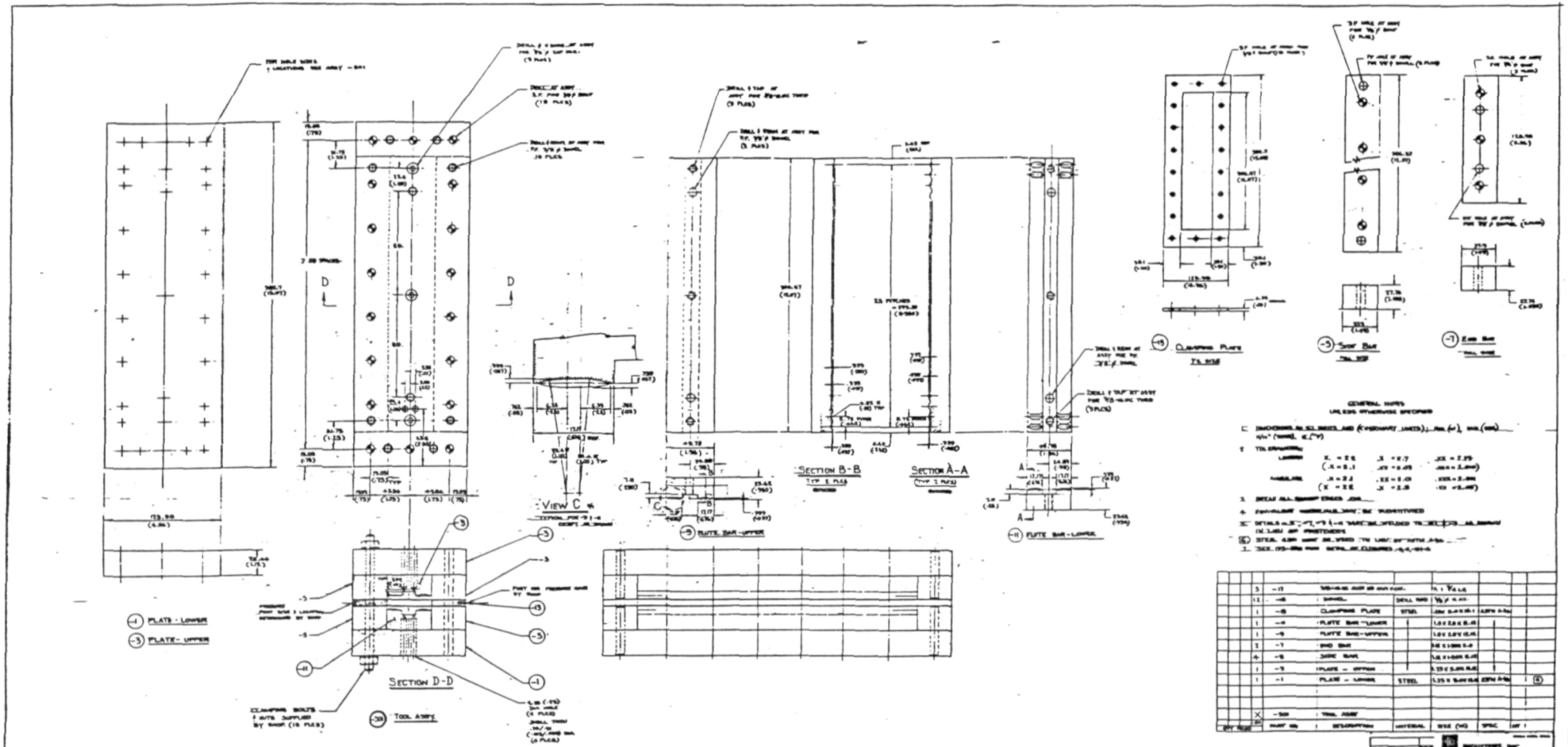


Figure 5. SPF Form Tool for Forming Edge Closures

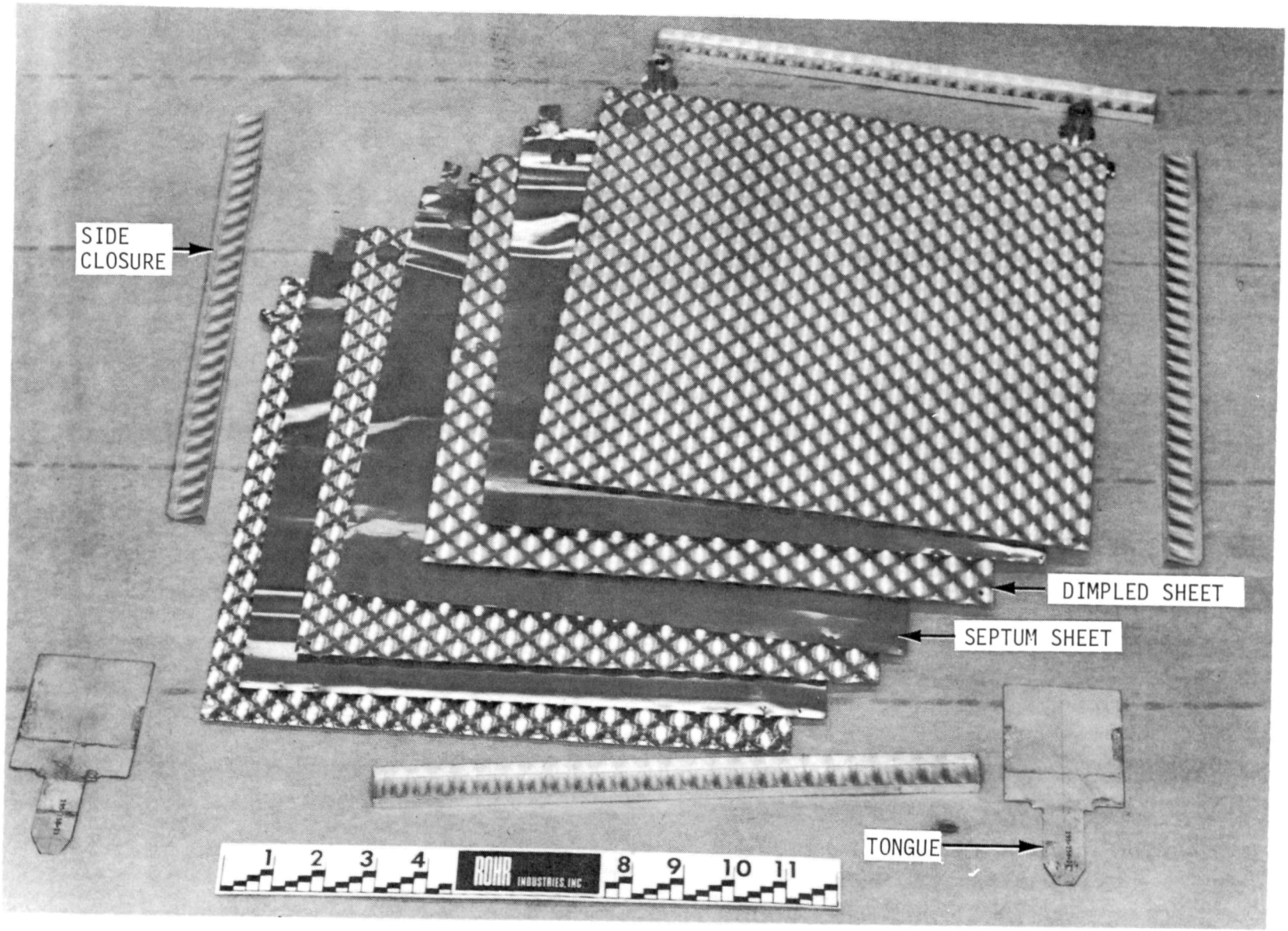


Figure 6. Detail Parts for Panel Having Thru Panel Fasteners and Tongues

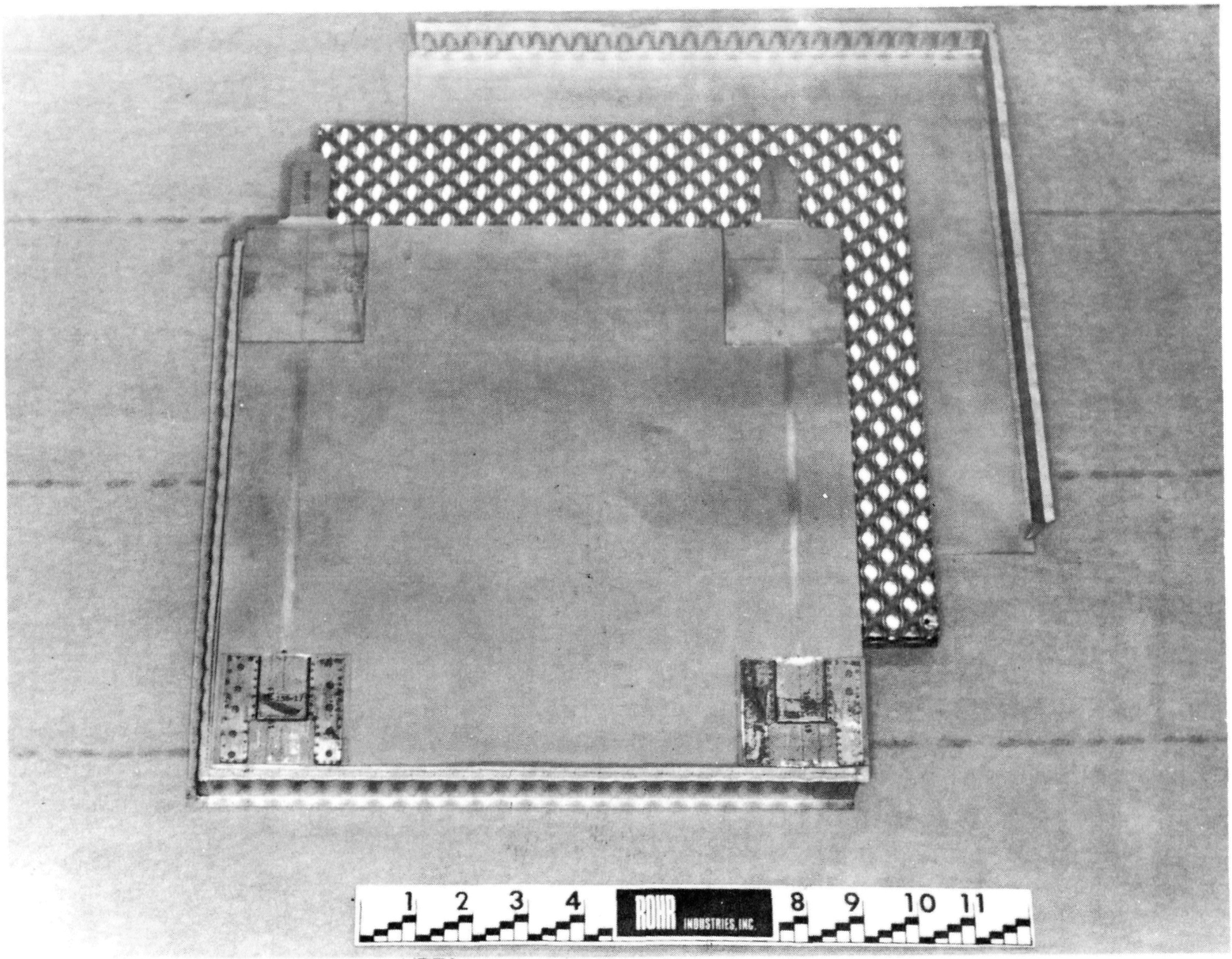


Figure 7. Multi-Wall Panel Containing Clips and Tongues Being Laid Up for LID Bonding

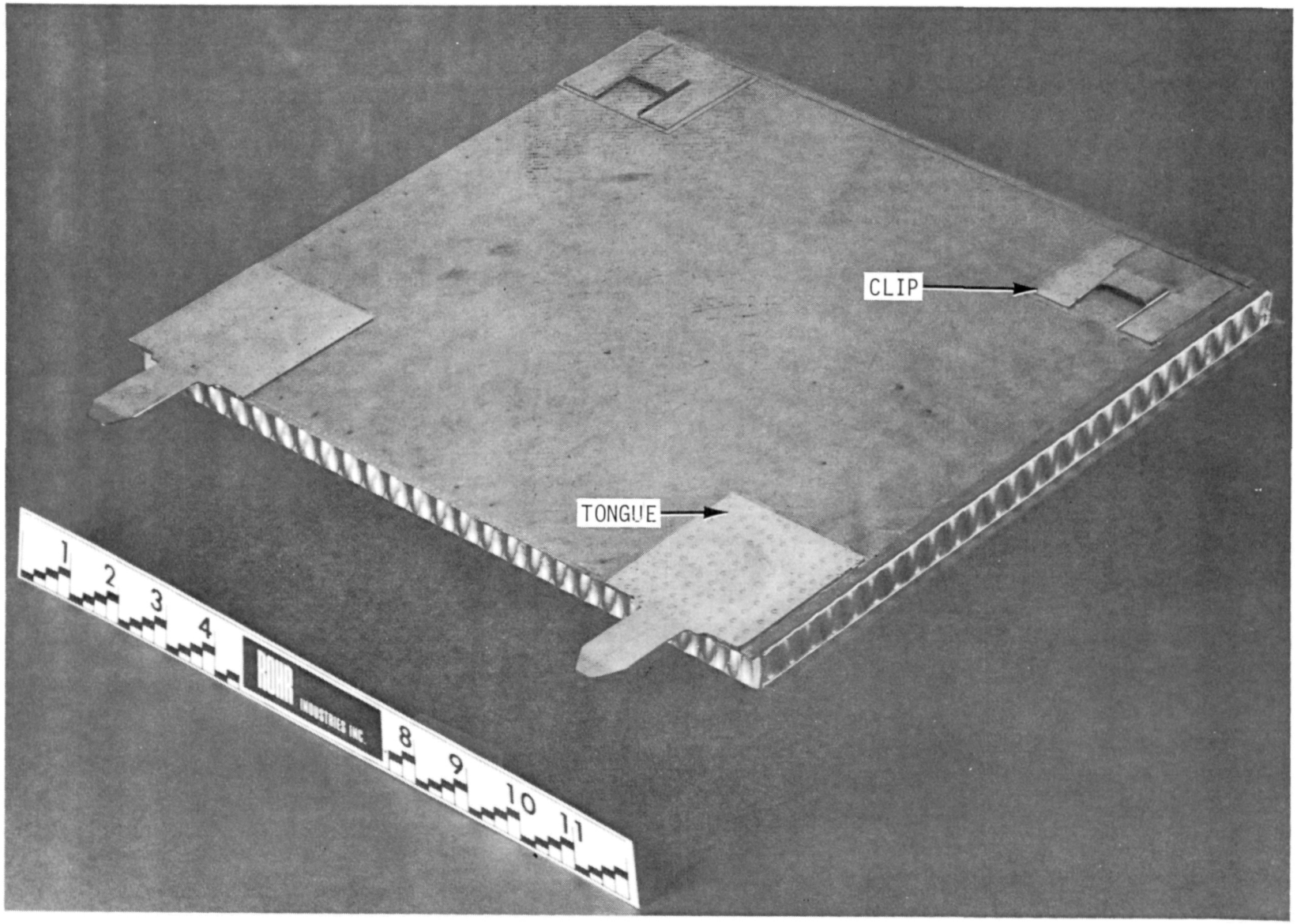


Figure 8. Panel Having Clips and Tongues Laid Up for Lid Bonding

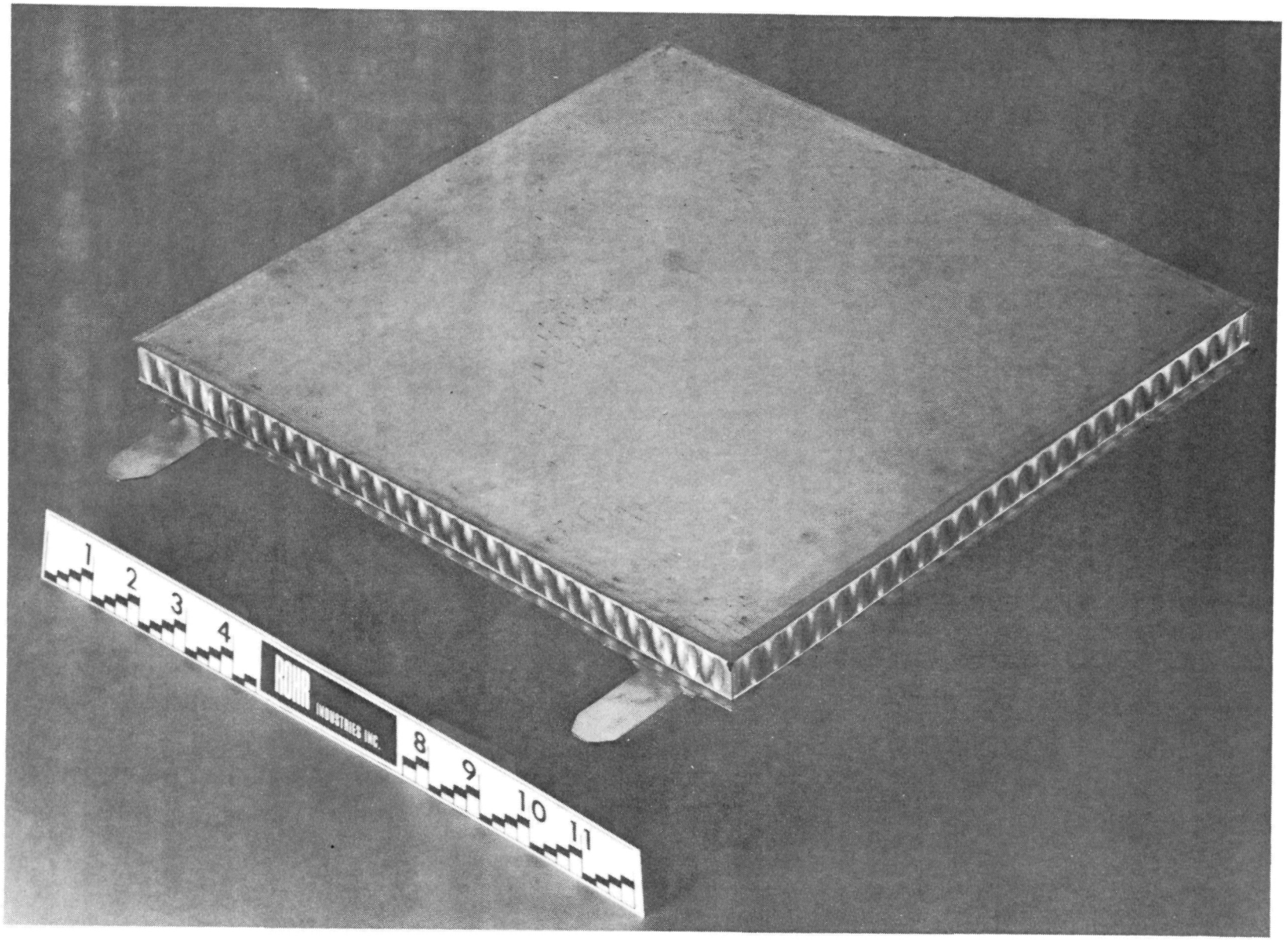


Figure 9. Top of Lid Bonded Panel Having Clips and Tongues

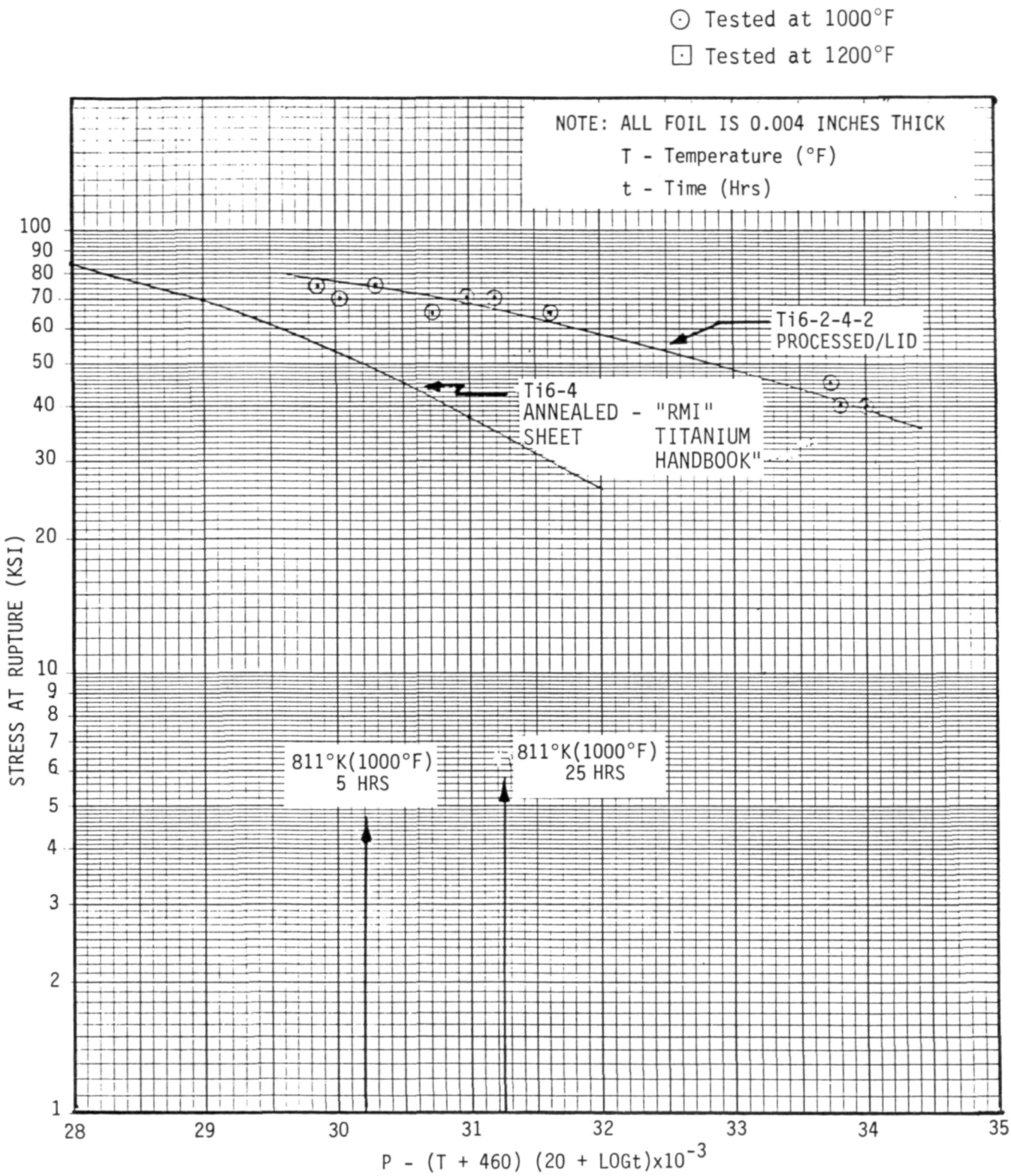


Figure 10. Larson-Miller Plot

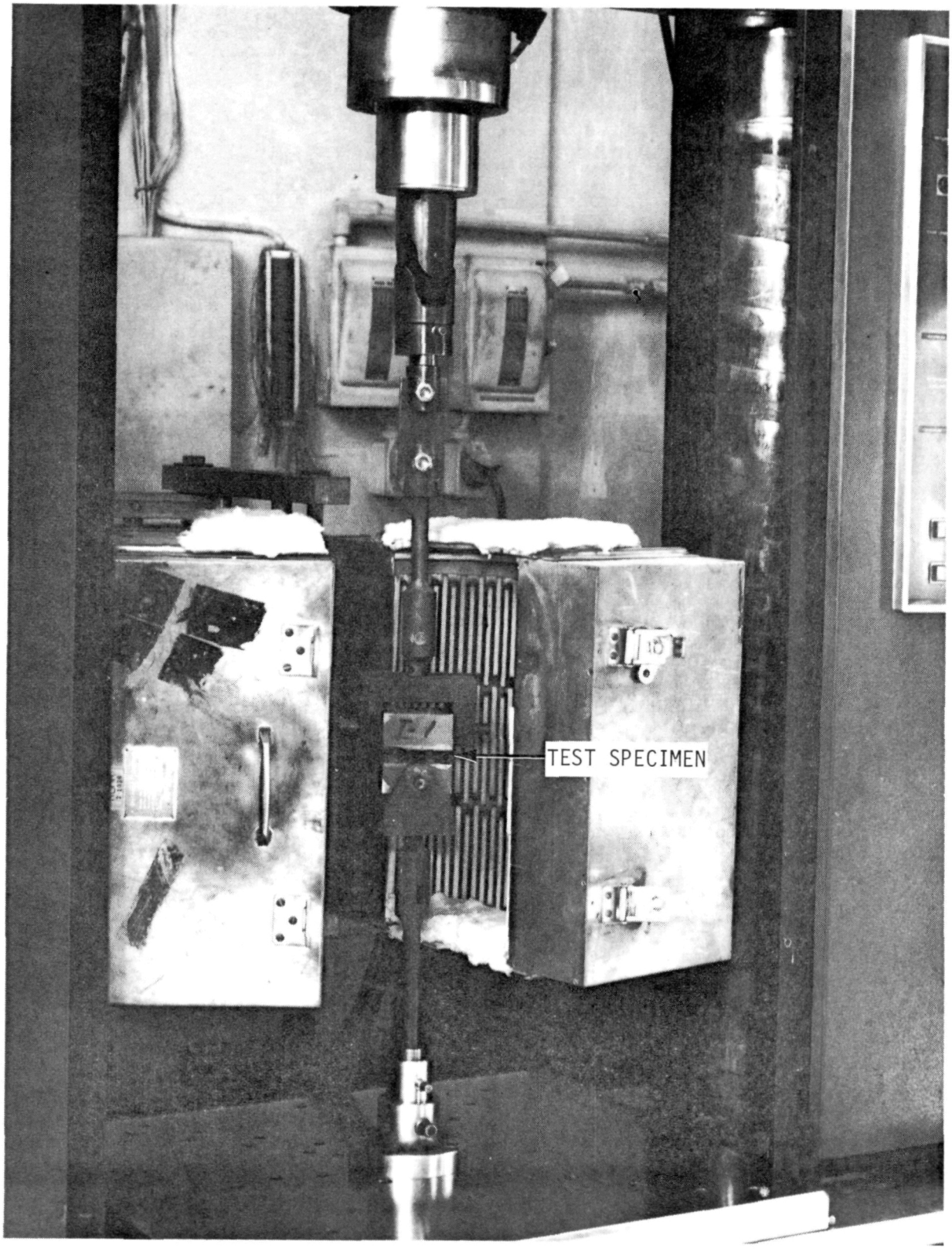


Figure 11. Test Fixture for Fatigue Tension Tests

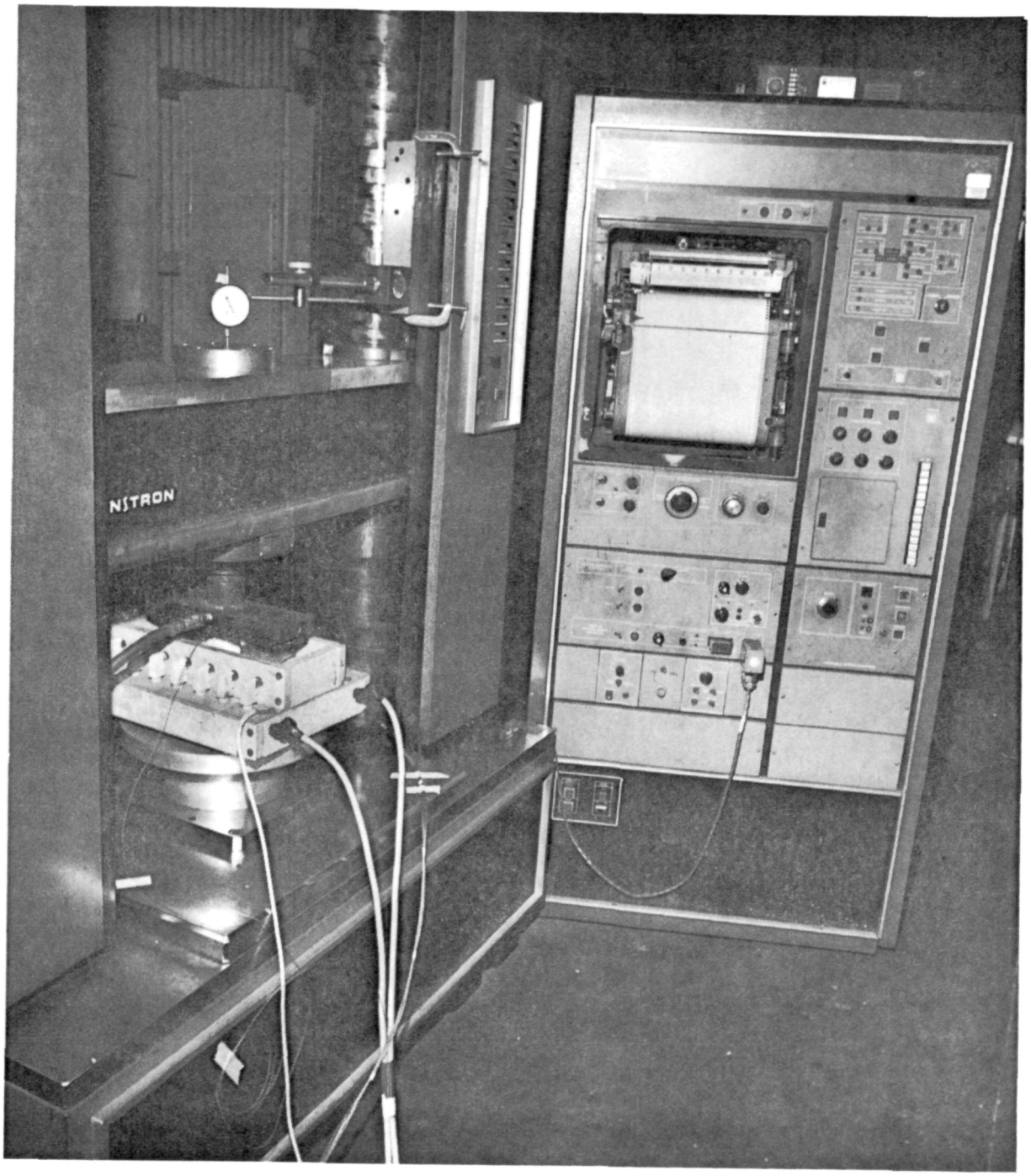


Figure 12. Test Setup for Beam Flexure Test

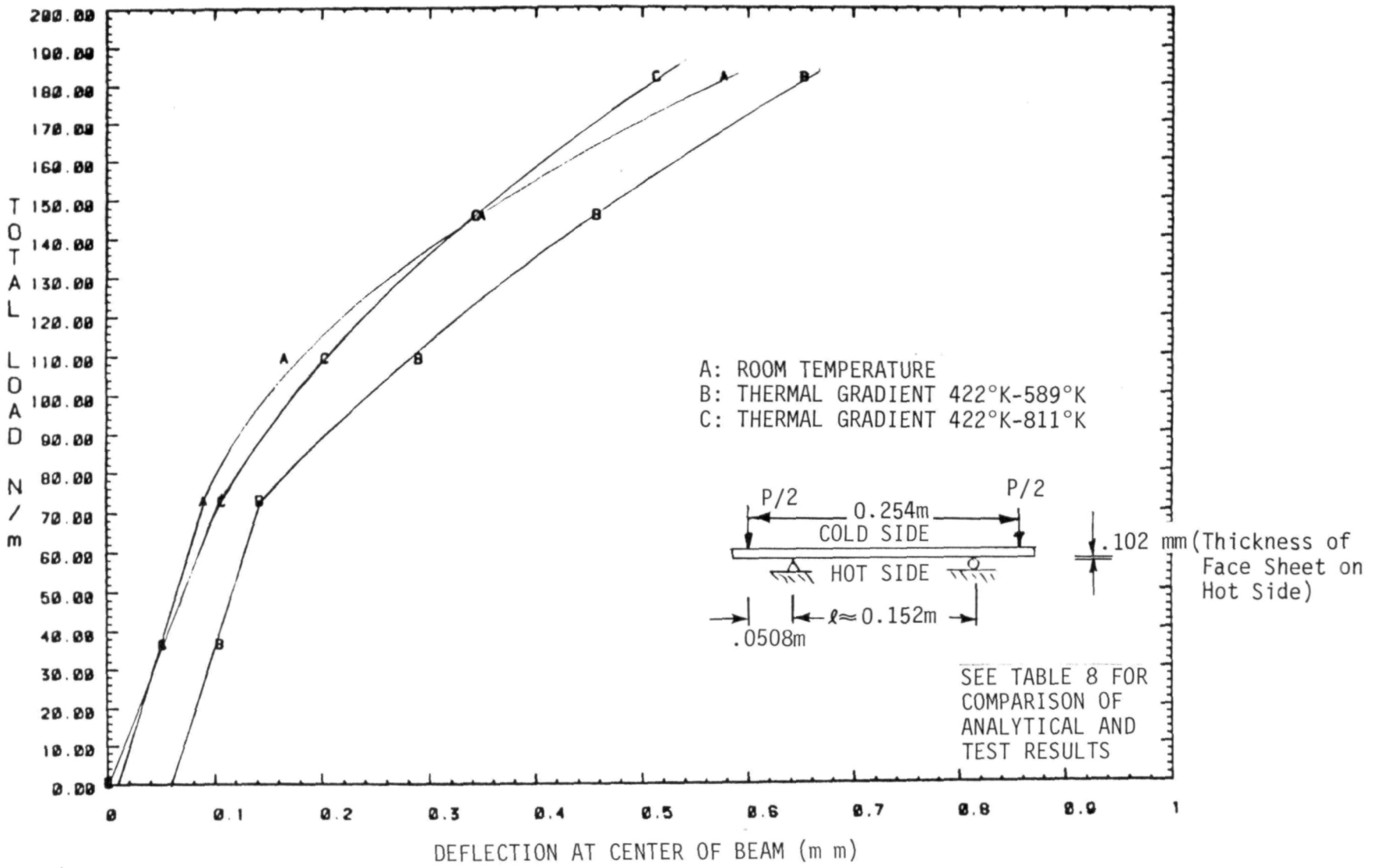


Figure 13. Beam Flexure Test Load Curves

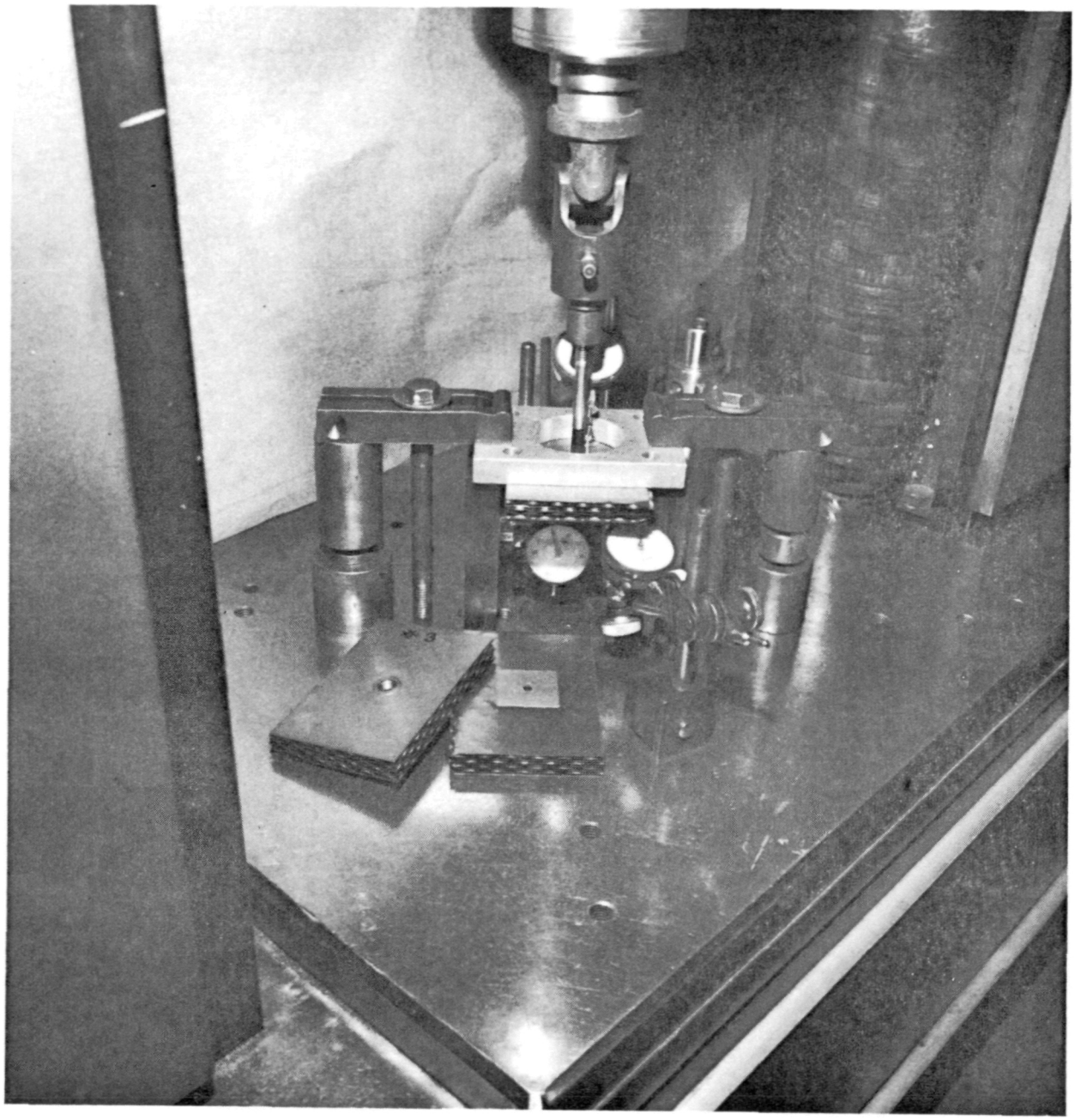


Figure 14. Test Setup of Thru Panel Fastener Test

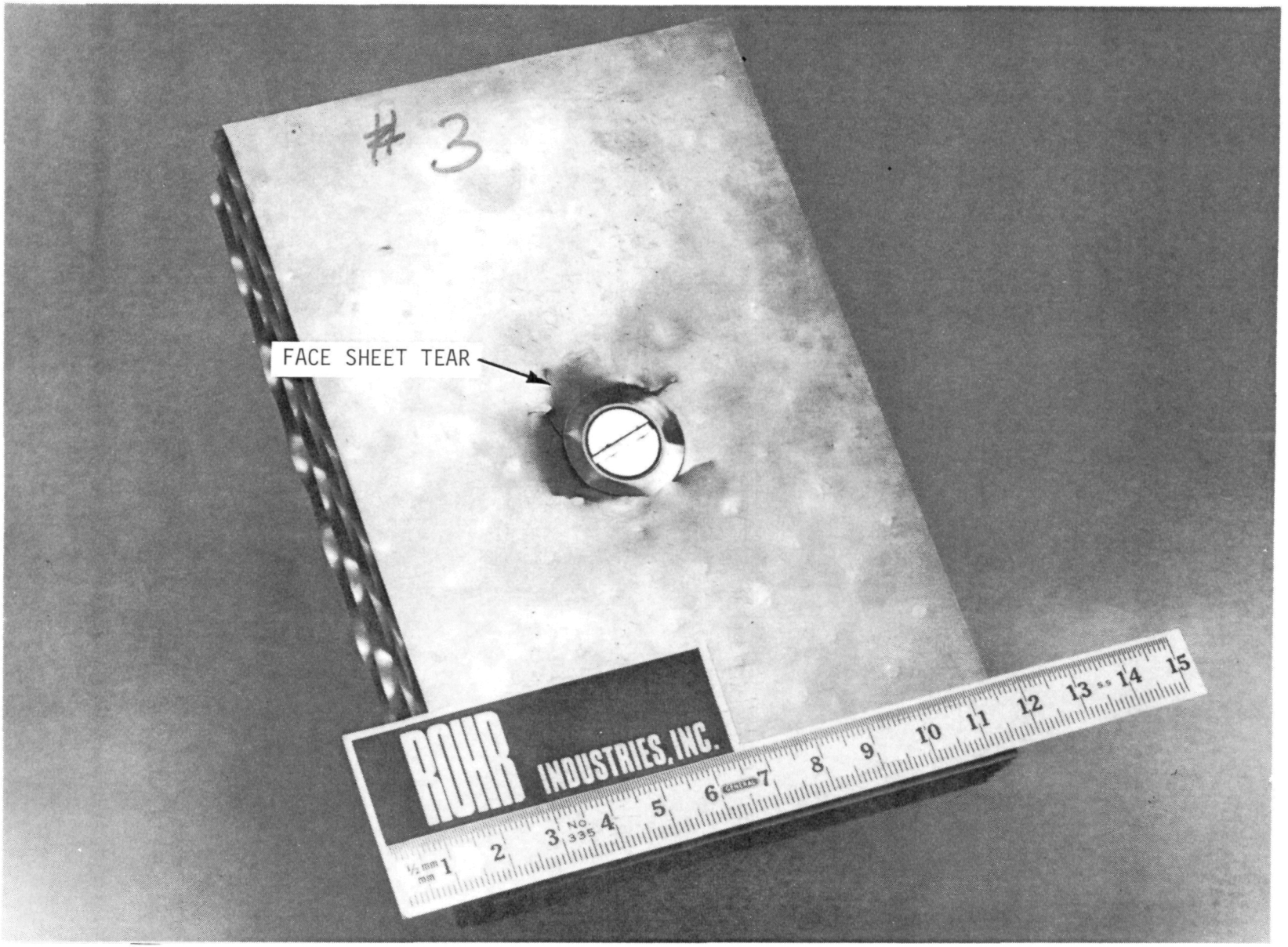


Figure 15. Typical Outer Face Sheet Tearout and Internal Panel Damage Failure Mode

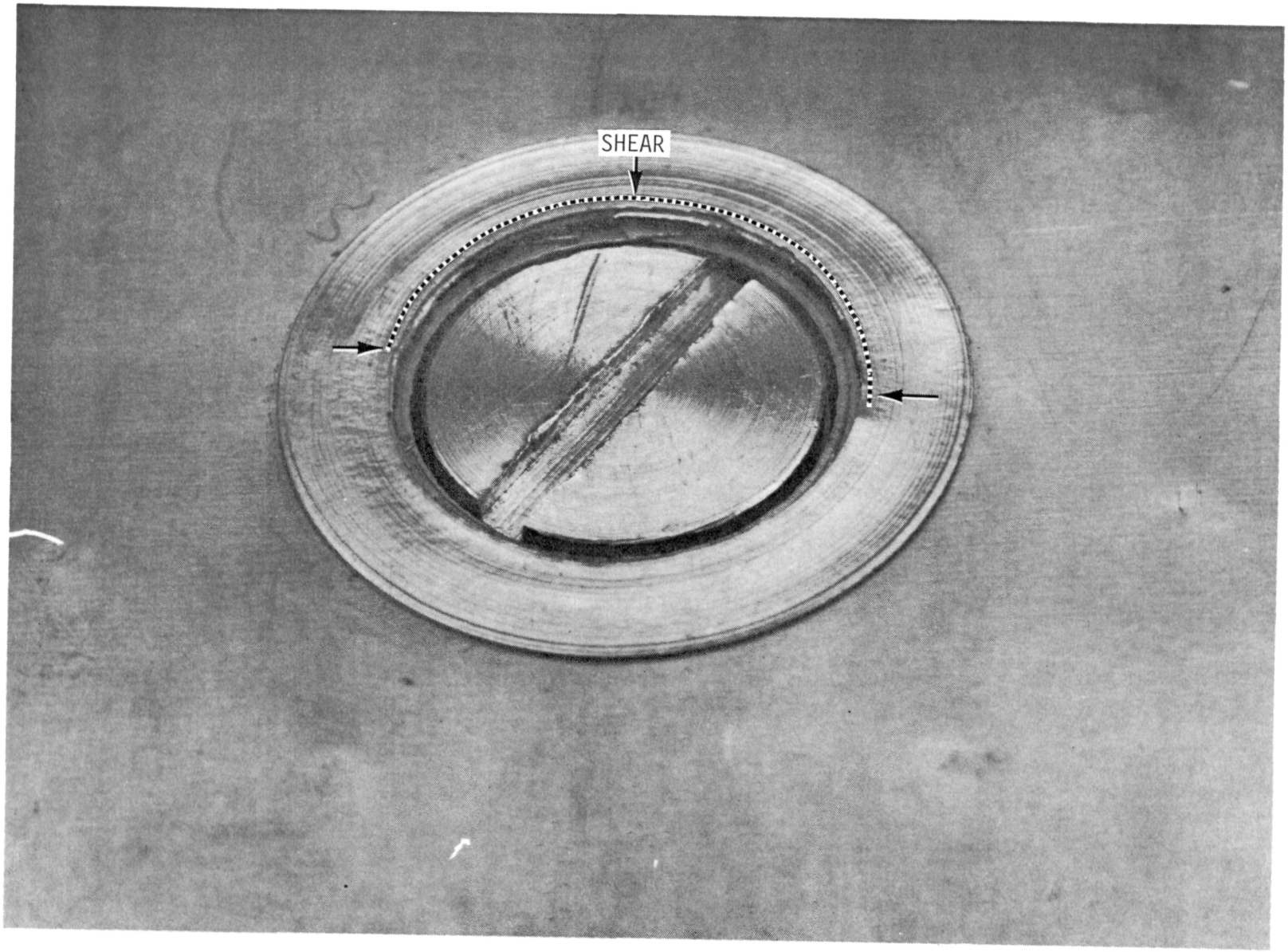


Figure 16. Typical Shear of Fastener Insert Flange Failure Mode

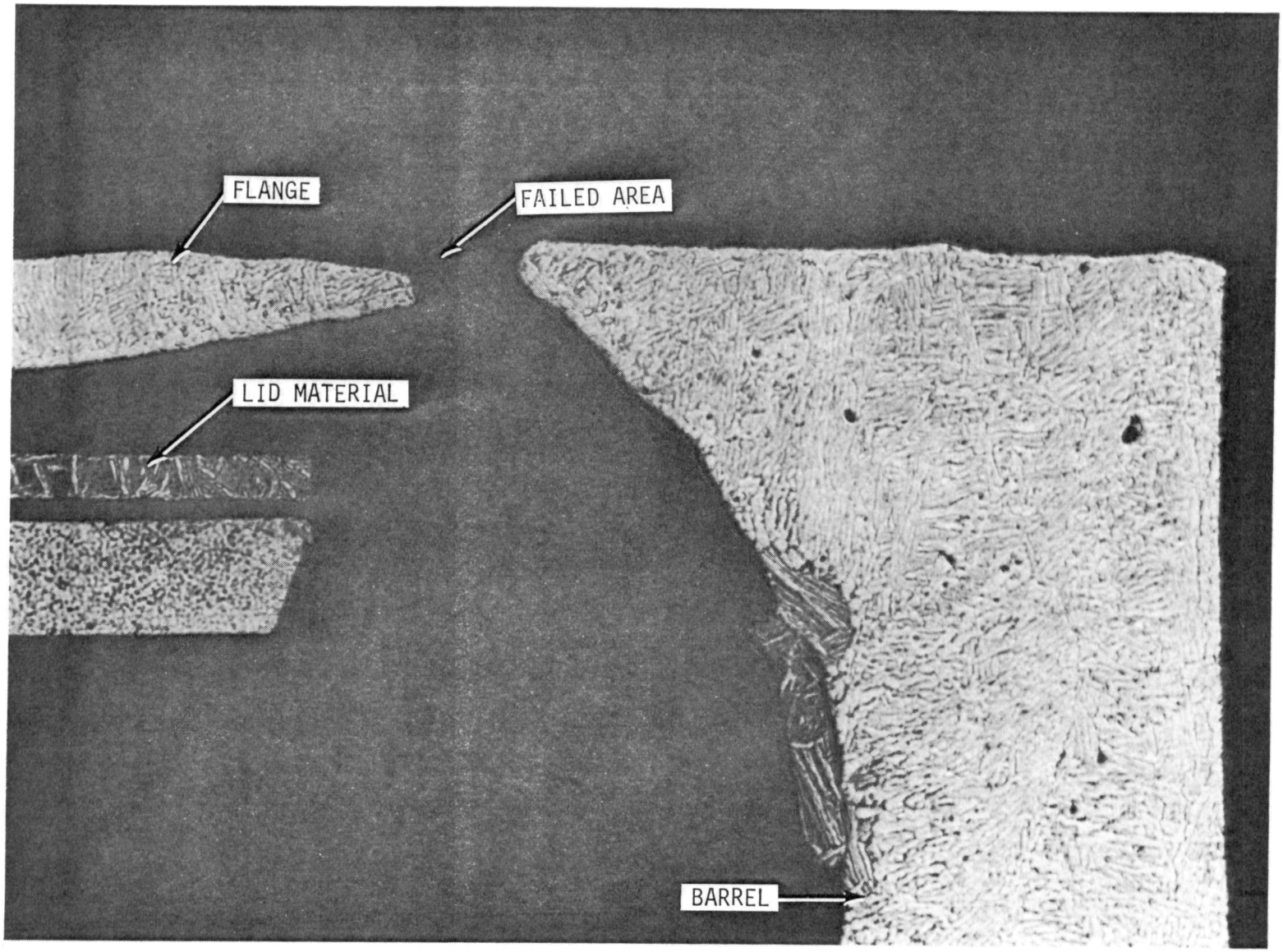


Figure 17. Photomicrograph Shows Over-machining of Fastener Insert Flange

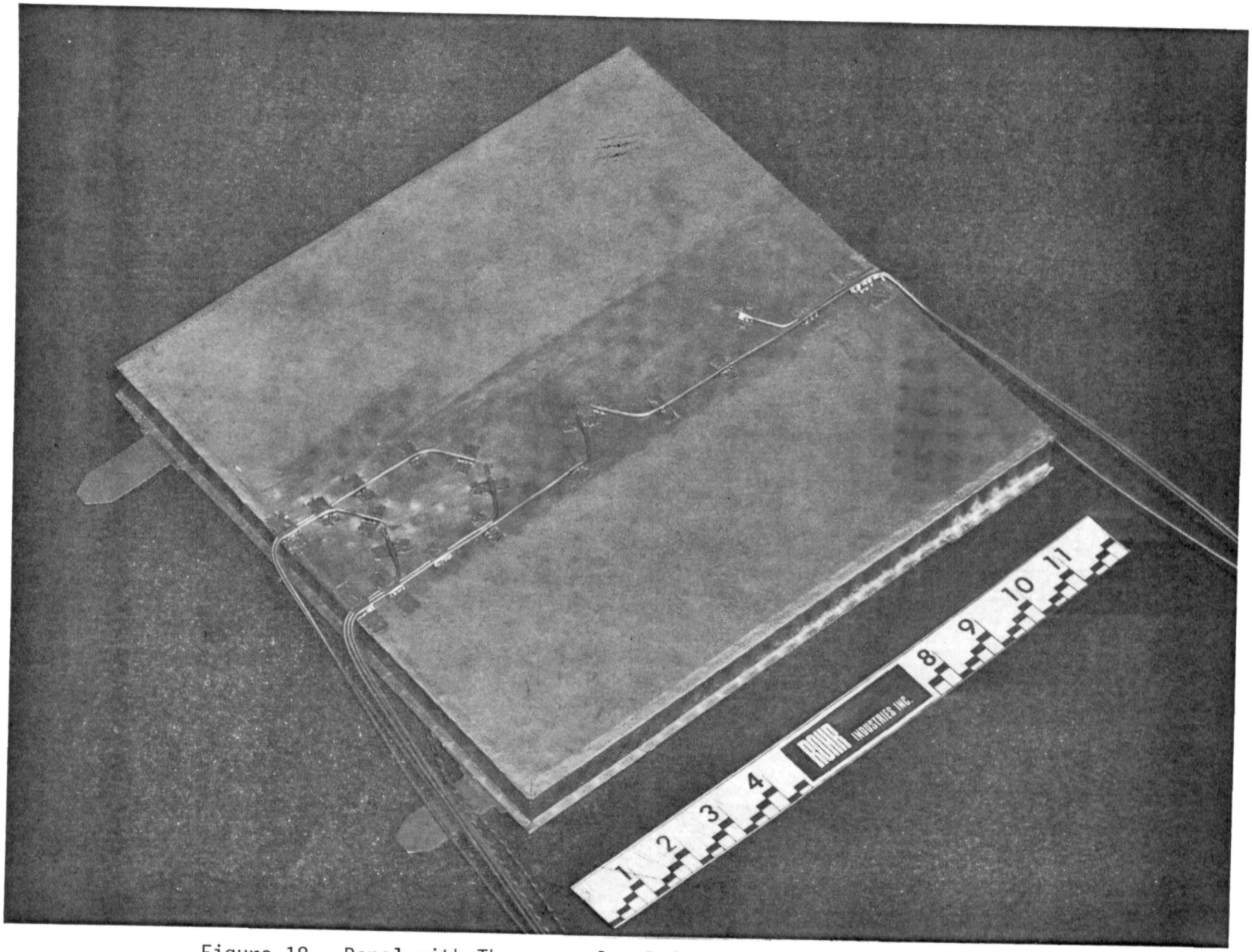


Figure 18. Panel with Thermocouples Being Prepared for Pressure Tests

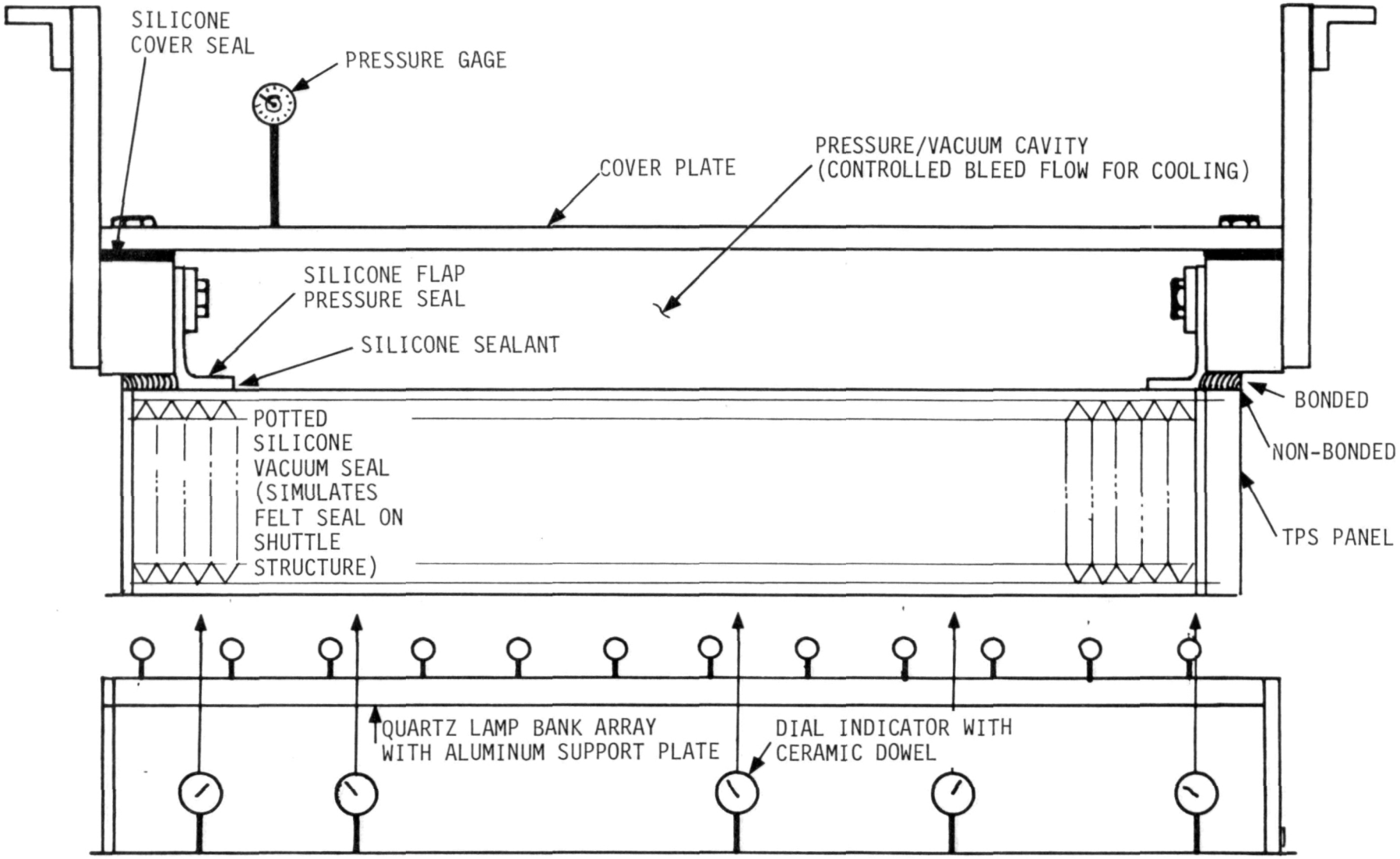


Figure 19. Schematic of Text Fixture for Thermal/Pressure Gradient

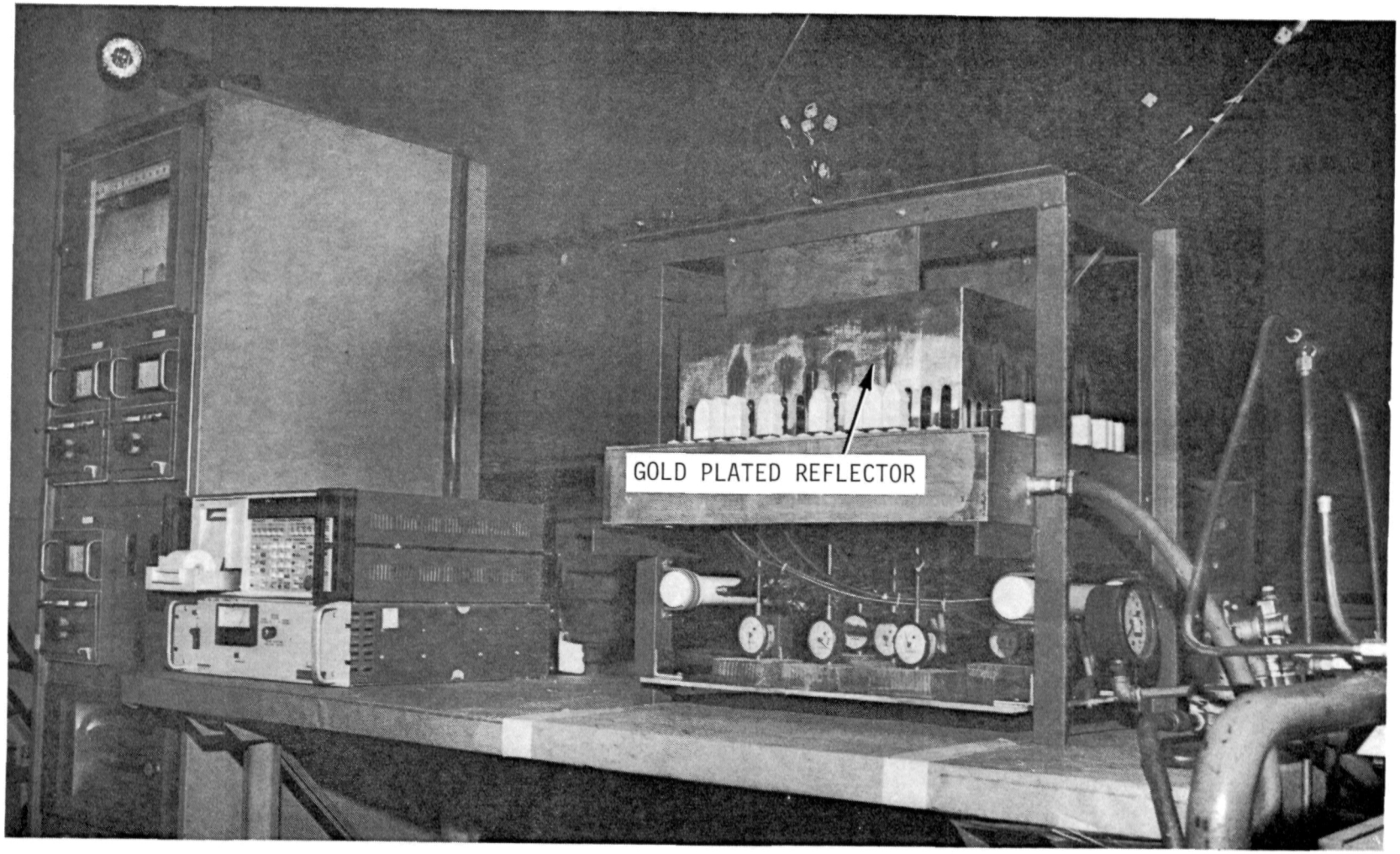


Figure 20. Shows the Complete Apparatus Use for Pressure Testing Panels While a Thermal Gradient is Applied

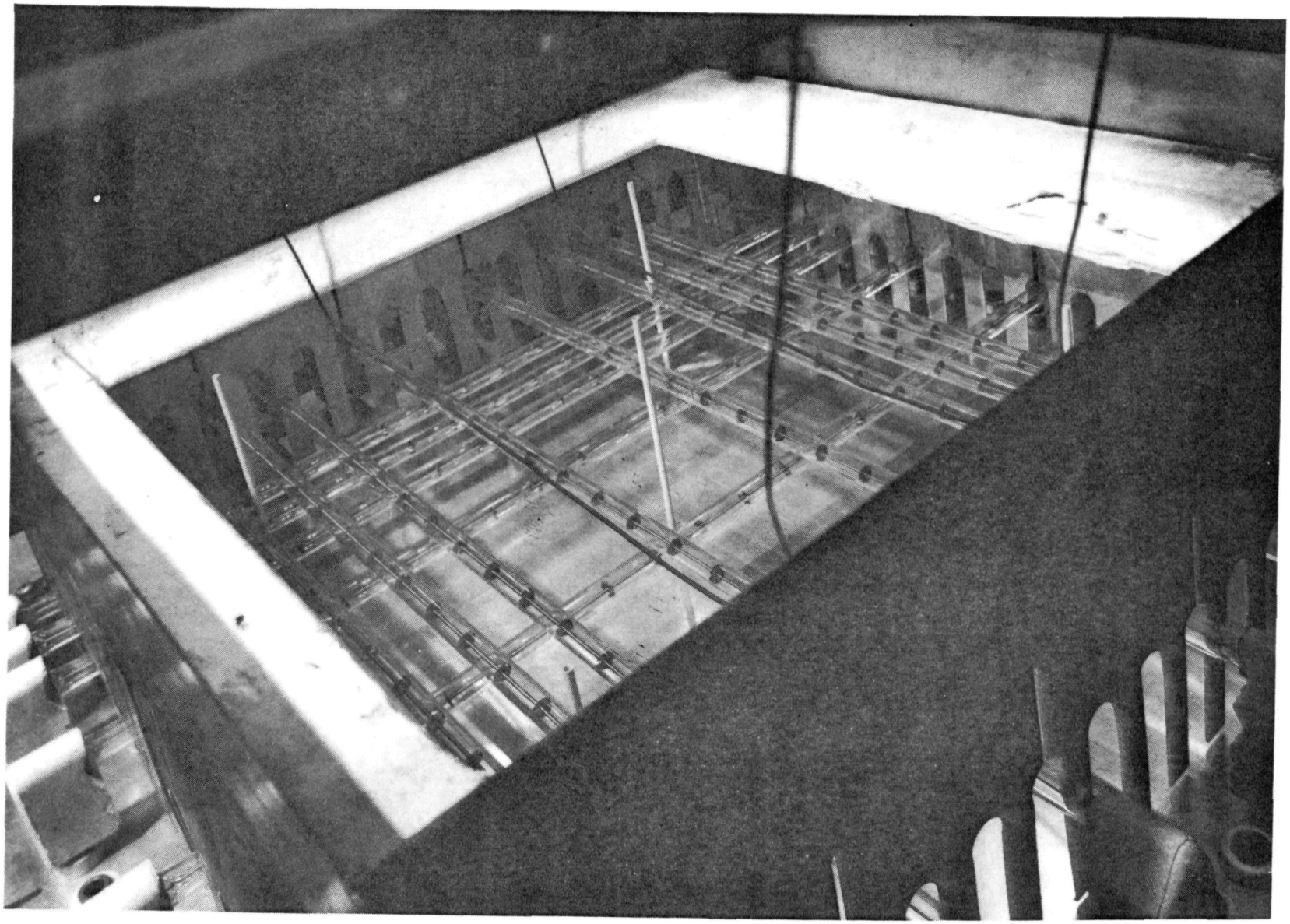


Figure 21. Zoned Quartz Lamp Bank used to Heat the Panel

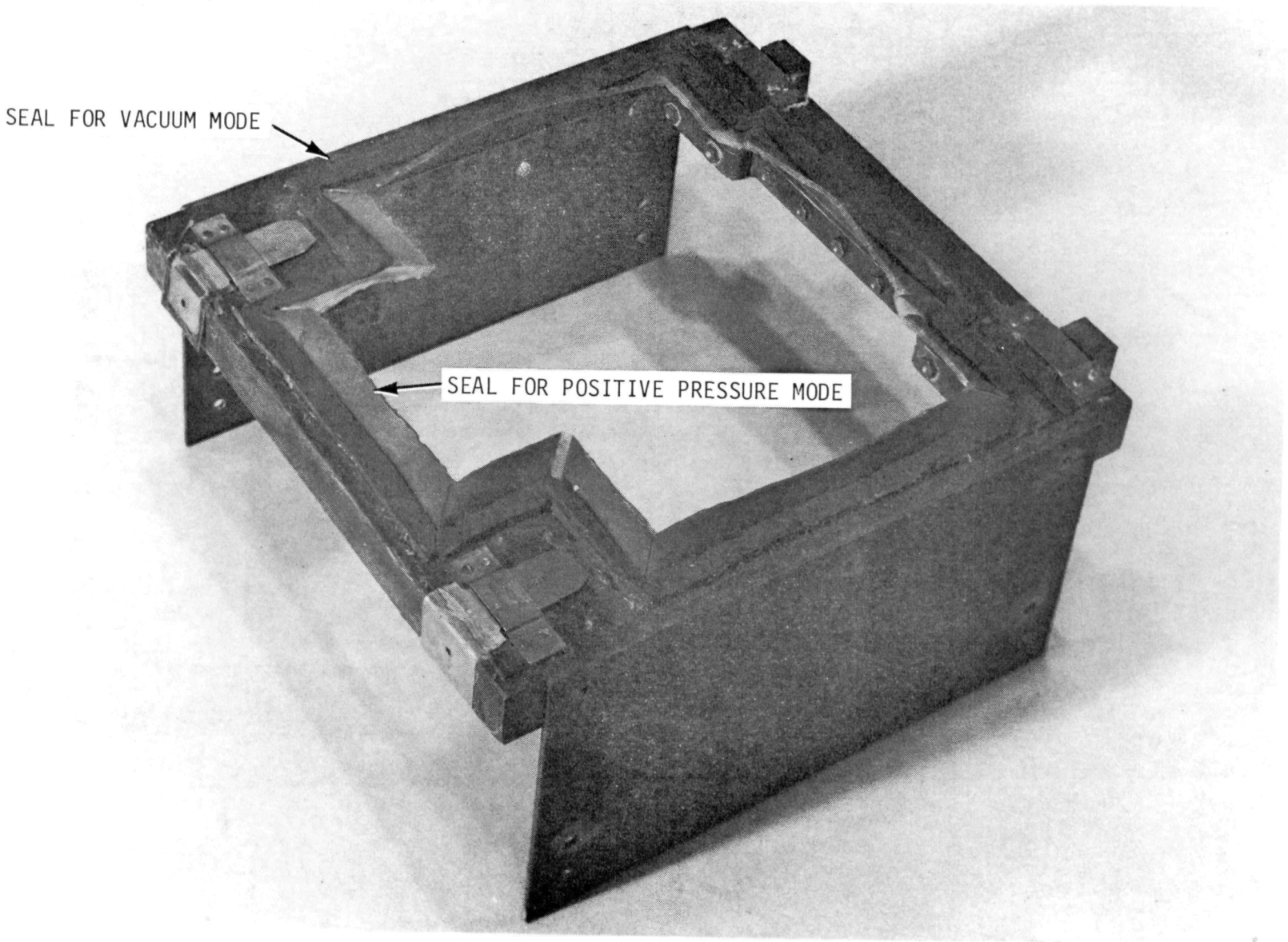


Figure 22. Top of Pressure Test Fixture

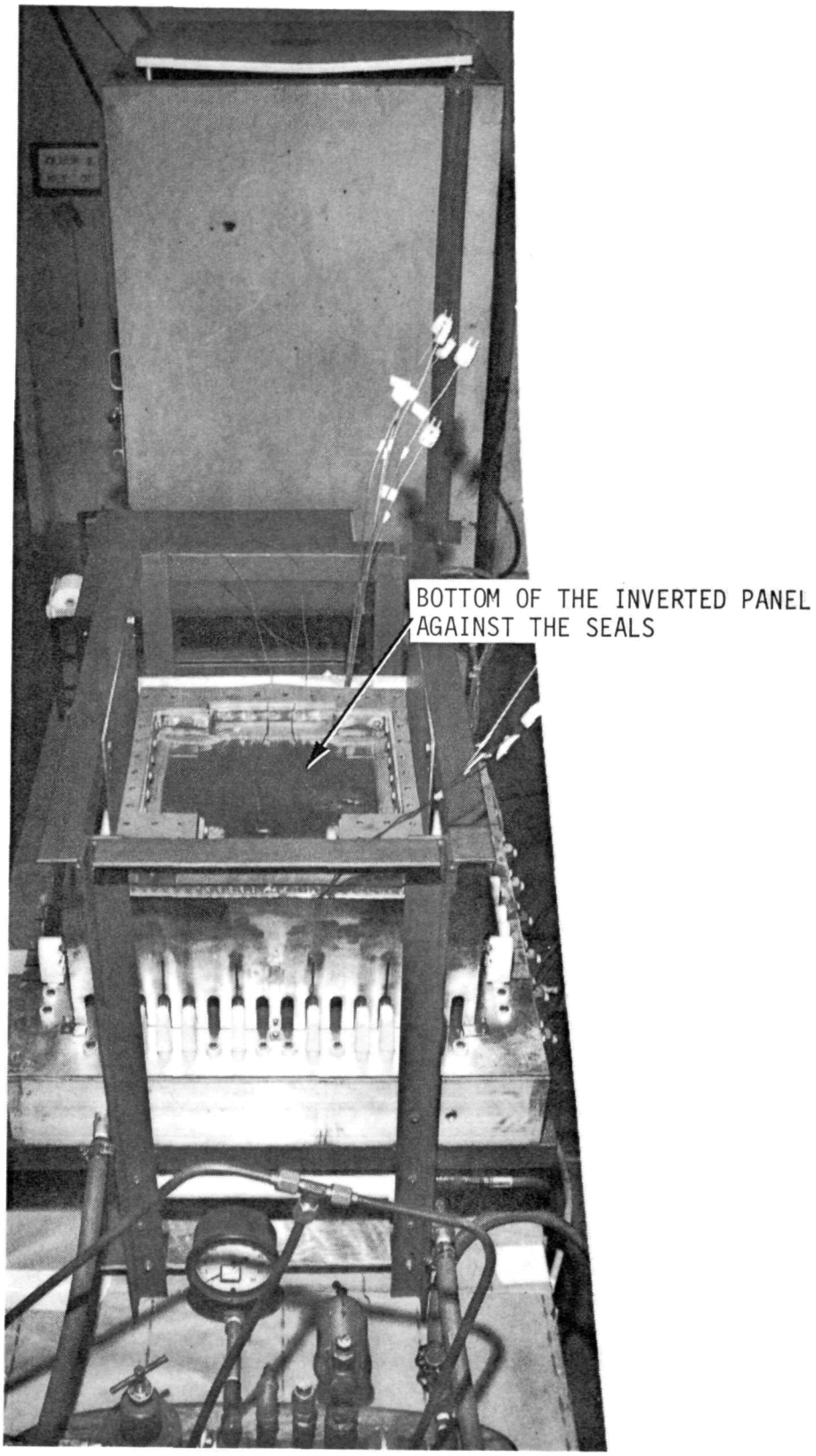


Figure 23. Bottom of the Inverted Panel Against the Seals

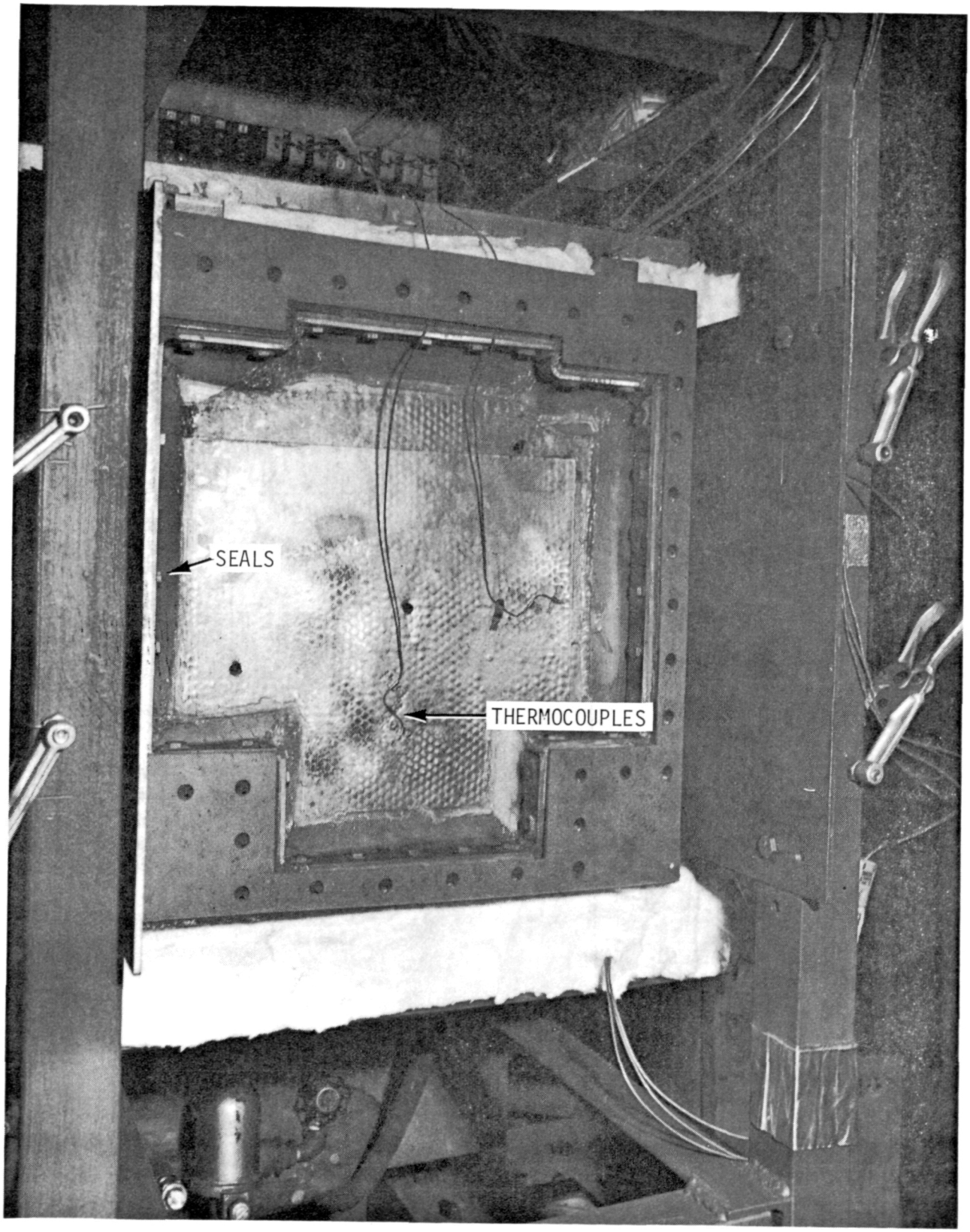
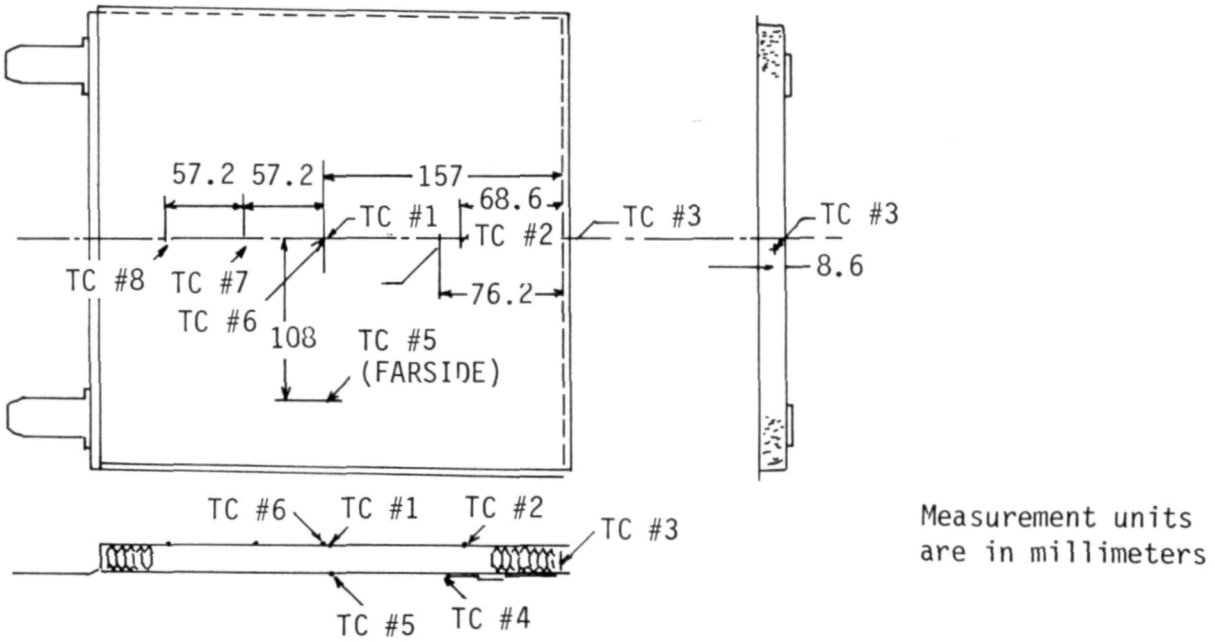


Figure 24. Panel Against the Seals. The Cover Plate is Removed

(8) THERMOCOUPLES
(6) DIAL INDICATORS
CONTROLLED HEAT UP RATES

CONDITION I	ROOM TEMPERATURE	4.6 KPa (.67 PSI) BURST
CONDITION II	ROOM TEMPERATURE	4.6 KPa (.67 PSI) CRUSH
CONDITION III	810.9°K/422°K (1000°F/300°F)	4.6 KPa (.67 PSI) BURST
CONDITION IV	810.9°K/422°K (1000°F/300°F)	4.6 KPa (.67 PSI) CRUSH
CONDITION V	810.9°K/422°K (1000°F/300°F)	20.7 KPa (3.00 PSI) BURST
CONDITION VI	810.9°K/422°K (1000°F/300°F)	0.0 KPa (0.0 PSI)

Figure 25. Titanium Multi-Wall Panel Pressure-Thermal Gradient Test



CASE V	TEMPERATURE°K *							
PRESSURE KPa (PSI)	1	2	3	4	5	6	7	8
0	832	827	638	499	494	831	830	816
+3.4 (+.50)	822	820	625	411	455	820	820	813
+6.89 (+1.00)	808	816	593	384	415	805	804	808
+10.3 (+1.50)	819	822	563	374	396	818	814	814
+13.8 (+2.00)	820	820	493	364	381	818	810	812
+17.2 (+2.50)	825	816	439	355	369	823	821	815
+20.7 (+3.00)	820	802	420	346	358	820	817	811

*°F = 1.8 (°K) - 459.67

Figure 26. Thermocouple Location & Temperature Profile

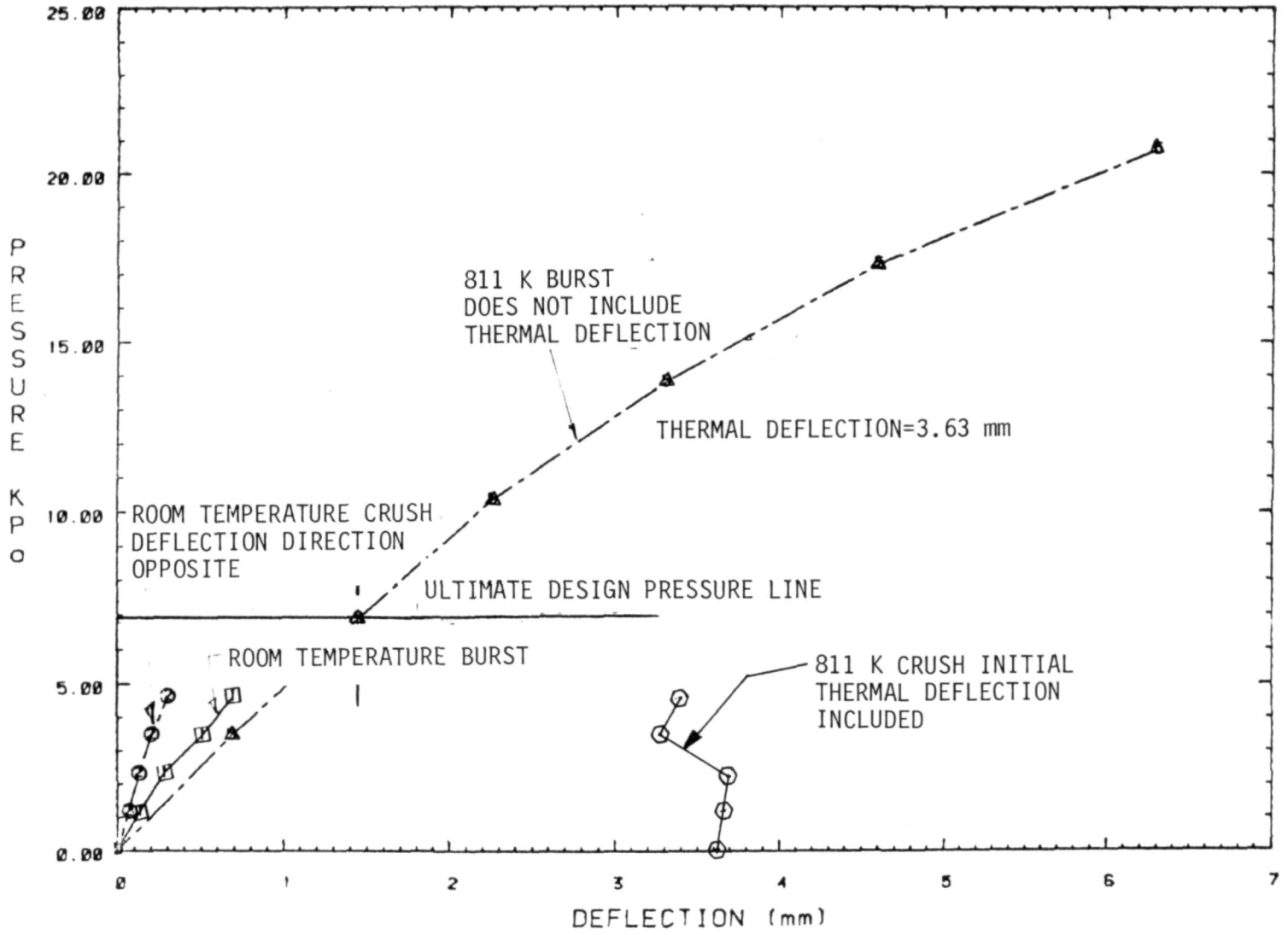


Figure 27. Titanium Multiwall Panel Applied Pressure vs Center Panel Deflection for Various Loading Conditions

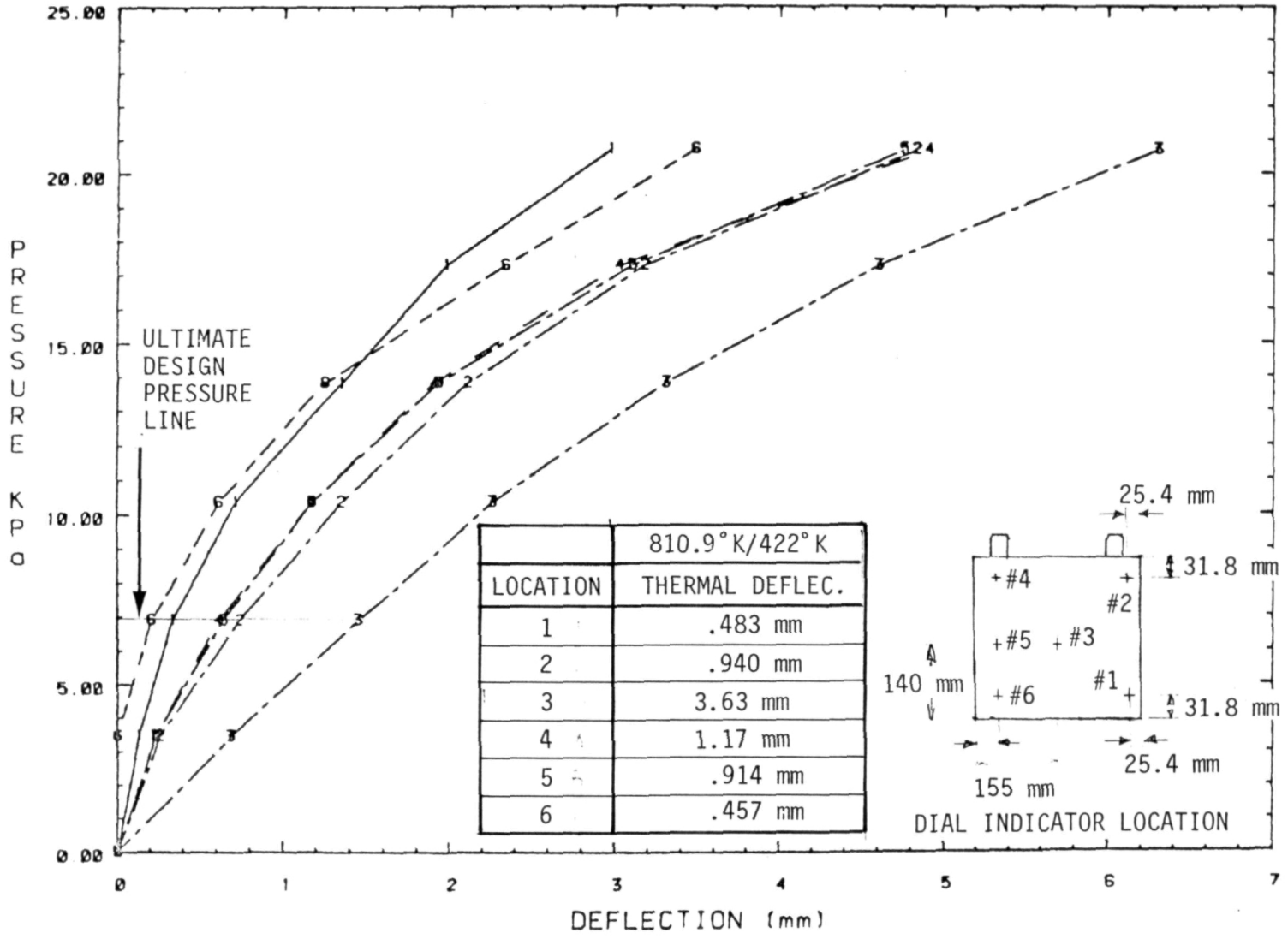


Figure 28. Titanium Multiwall Panel Deflection Due to Pressure Only @ 811° K/422°K Gradient

LOADING CONDITION	LOCATION			
	CENTER OF PANEL		MIDDLE OF EDGE OF PANEL	
	mm	(in)	mm	(in)
I. ROOM TEMPERATURE 4.6 Kpa BURST				
ANALYTICAL	.940	(.037)	.800	(.0315)
TEST	.711	(.028)	.406	(.016)
II. ROOM TEMPERATURE 4.6 Kpa CRUSH				
ANALYTICAL	.0737	(.0029)	.0203	(.0008)
TEST	.305	(.012)	.102	(.004)
VI. 811 K/422 K				
ANALYTICAL	4.26	(.168)	2.36	(.0929)
TEST	4.70	(.185)	1.35	(.053)

NOTE: ANALYTICAL RESULTS ARE FROM 2-D NASTRAN FINITE ELEMENT MODEL

Figure 29. Panel Deflections

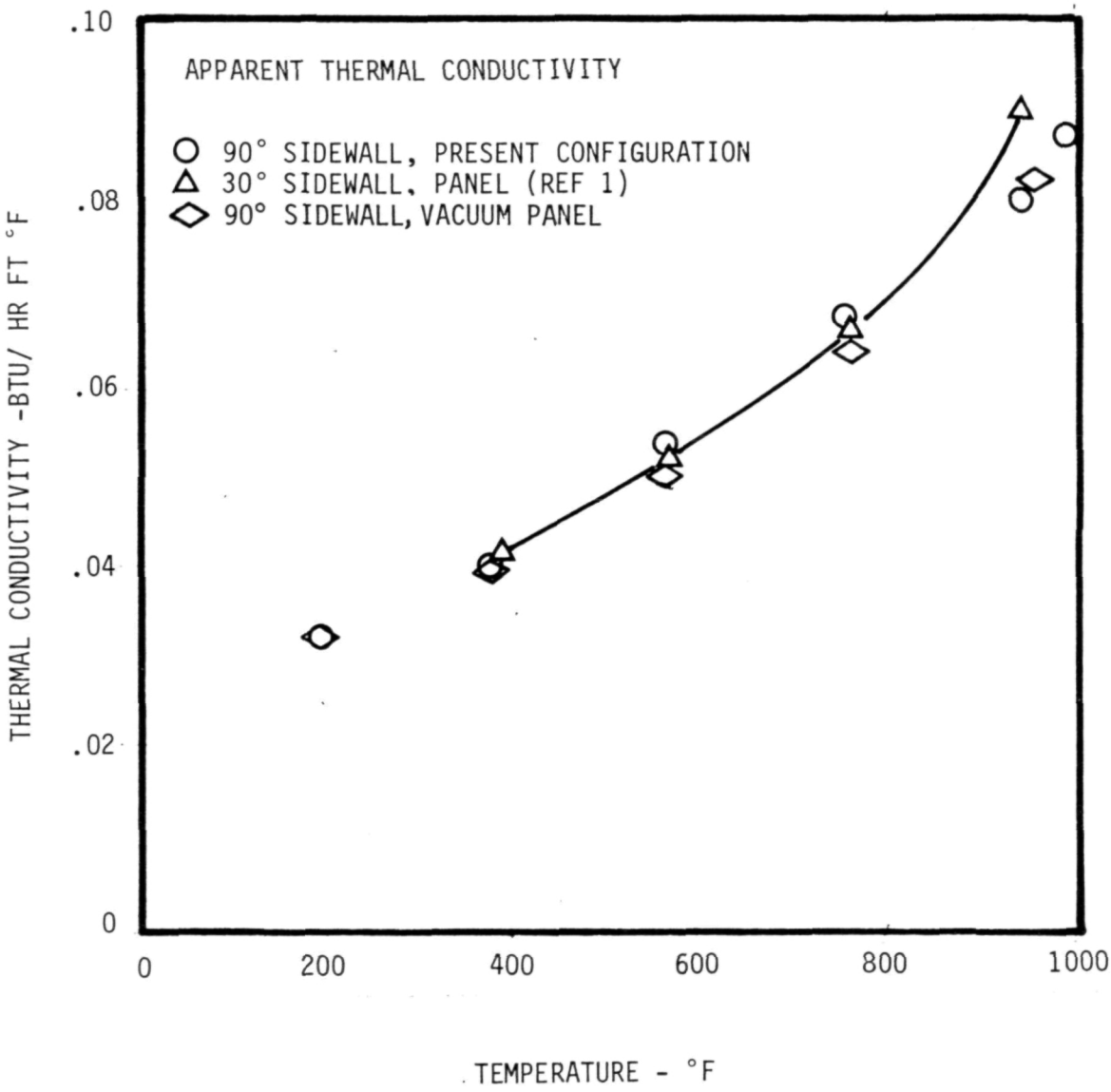


Figure 30. Apparent Thermal Conductivity of Titanium Multiwall Panel

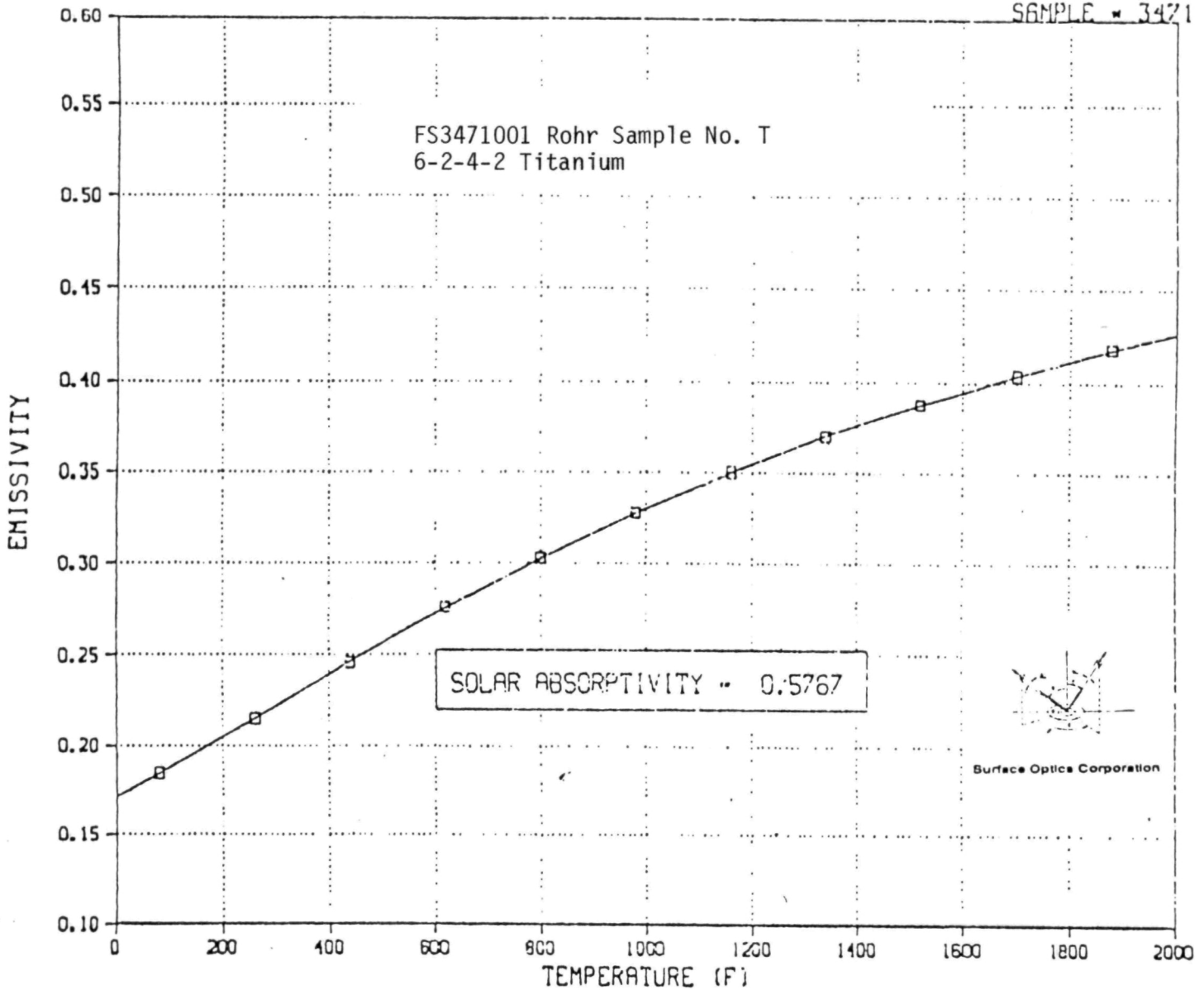


Figure 31. Emissivity vs Temperature

ROHR INDUSTRIES
PLANNING

PARTS AND OPERATION LOG

PLN. CC	PROJ.	MODEL	PART NAME	PART NUMBER	E C I	MFG. CD	ORIG. AUTH.
			(CLIP) TPS TASK VI	195-258-17			

ISSUE NUMBER	DATE	PSQ	SHIP EFFECTIVITY FROM	SHIP EFFECTIVITY THRU	AUTH.	VARIABLE PRE 0 1 2 3 4 5 6 7 8 9

MFG. & QA BUYOFF RUN STAMPS OPER.	FORE	LSON	OPER.	LOC DPT.	TP CC	QTY. BATT.	PART NUMBER / DESCRIPTION / TOOL/CUTTER CATALOG NUMBER (MT LC/DH SPEED/LG FEED/WD)	E C I T-GAGE	NAME SU OCCURS	REF. DWG. SPEC. TOOL CODE SU UNIT-RUN	SET-UP STAMPS OPER.	FORE
40			10	405			ISSUE TI-6AL-4V .025" X 2.1" X 2.5" (30 PCS). RECORD HEAT AND LOT NUMBER	955-5427		935-0263		
09579			20	405			PROCESS CLEAN PER RPS 11.88.					
84030			30	405			APPLY LF-22 FOR HOT FORMING PER RPS 15.45.					
84030			40	405			HOT FORM PER RPS 14.02.					
09579			50	405			PROCESS CLEAN PER RPS 15.45.					
P740			60	405			MACHINE PER 195-258-17 DRAWING.					
			70	405			DEBURR AND IDENTIFY ELECTROETCH 195-258-17 ON OUTSIDE OF CLIP.					
			80	723			INSPECT					
			90	829			STORE					

PAGE 1 OF 1

Figure 32. Typical Planning for Detail Parts Fab

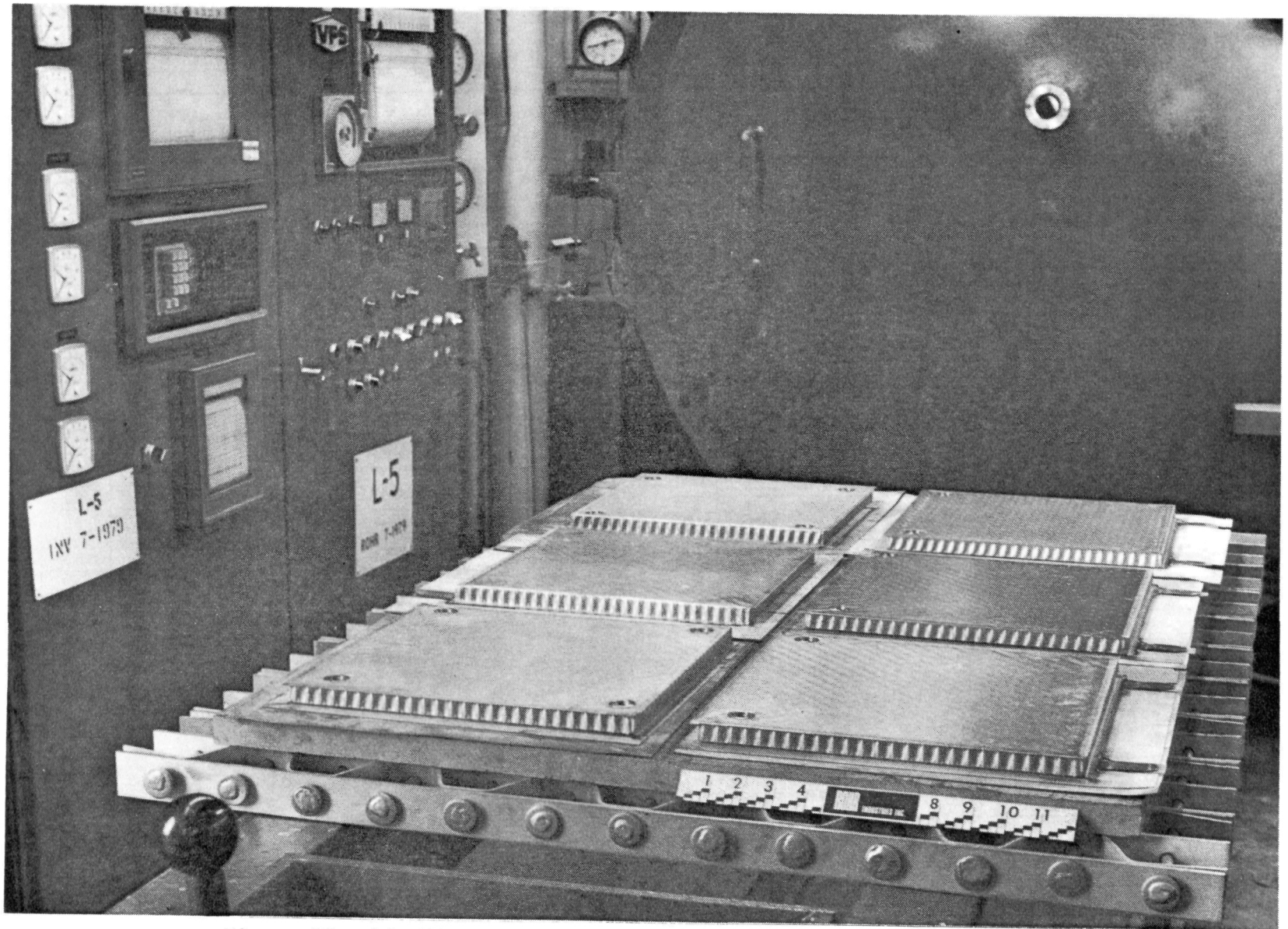


Figure 33. Six Titanium Multi-Wall Panels being Removed from Furnace after LID Bonding

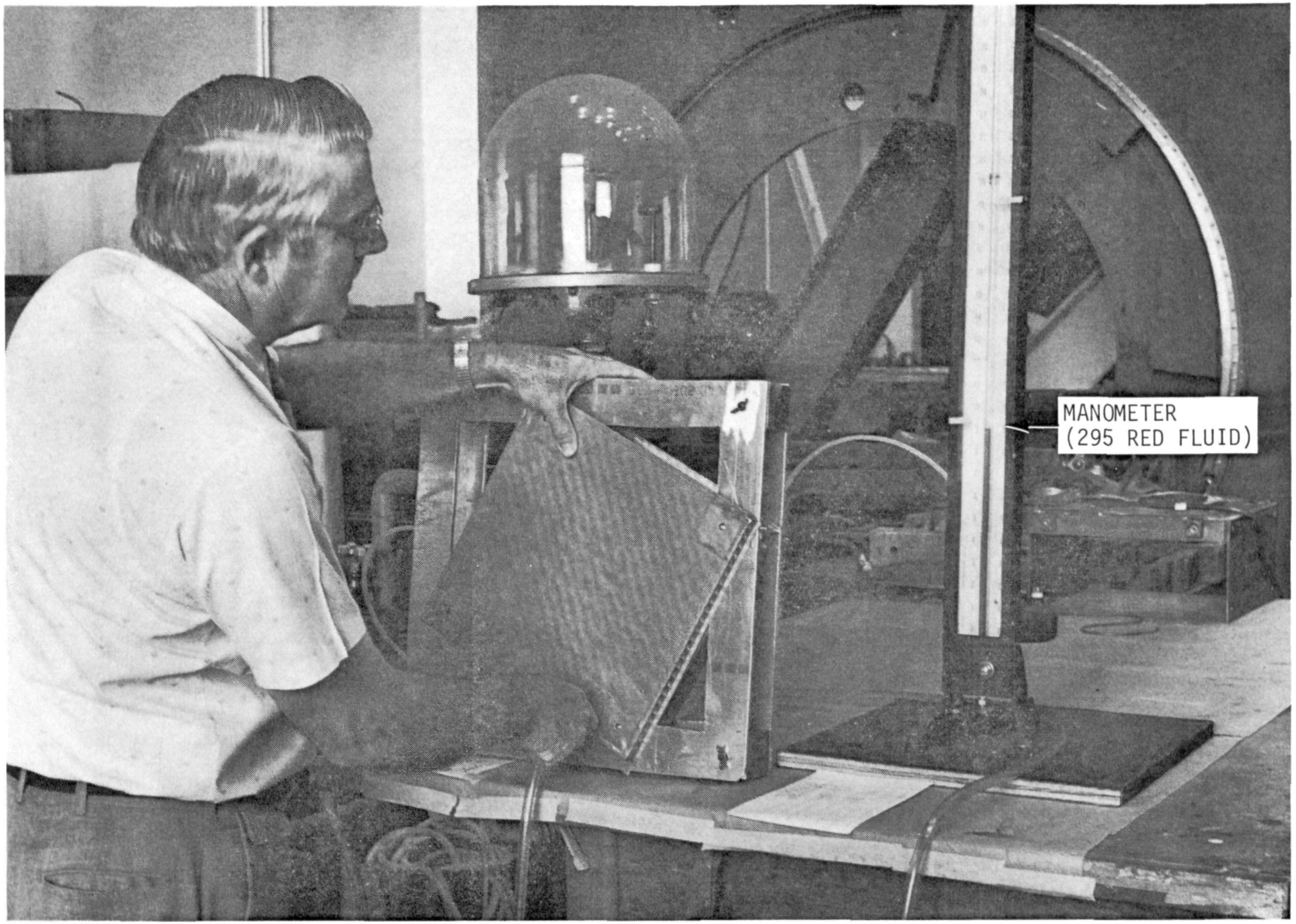


Figure 34. Multi-Wall Panel being Pressure Tested to 1 PSI Internal Pressure

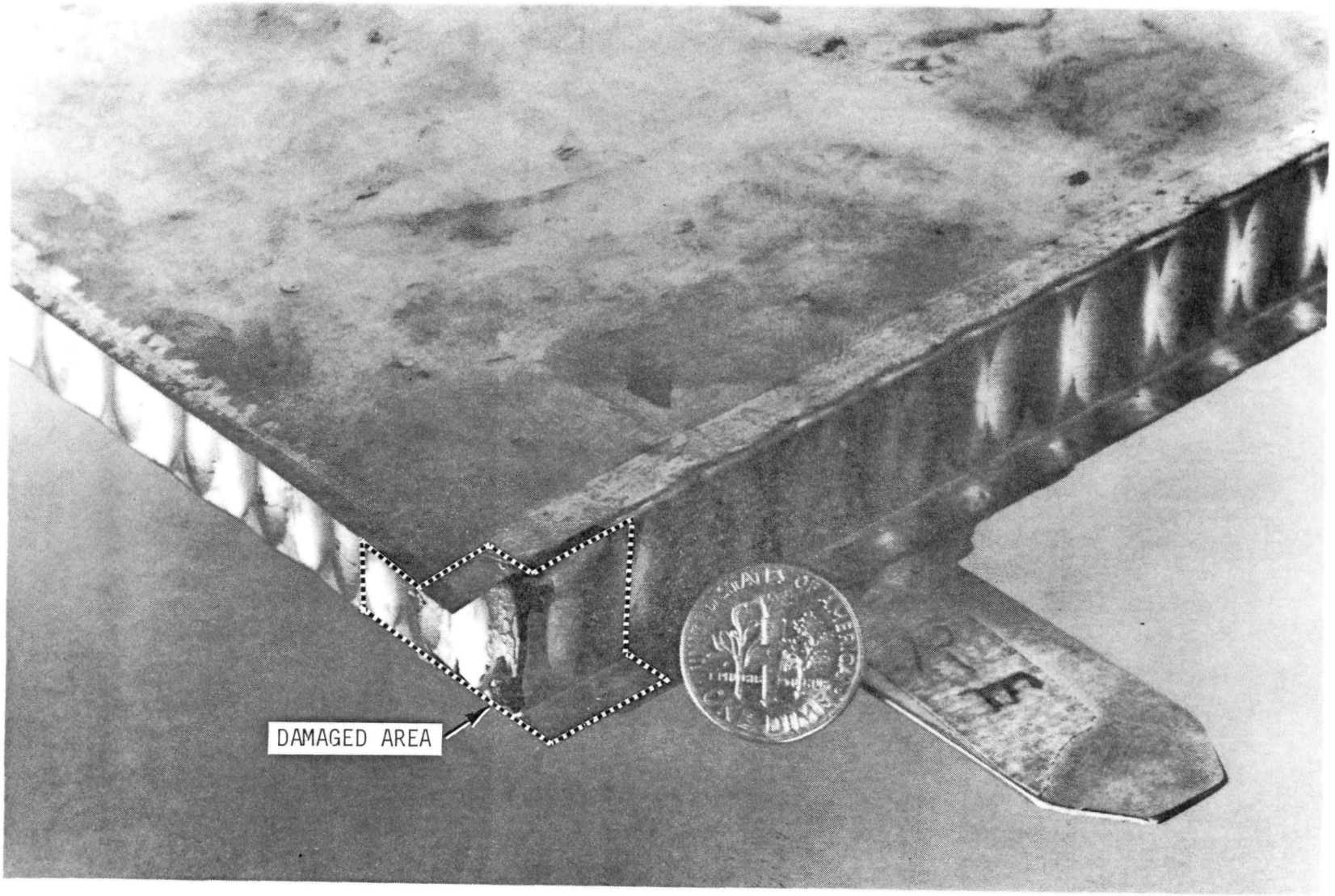


Figure 35. Damaged Corner of Panel

Figure 36. Panel was Repaired after Damage

Figure 37. Crease in Bottom Skin 0.41mm (0.016 inch) Deep by 152mm (6 Inches Long)

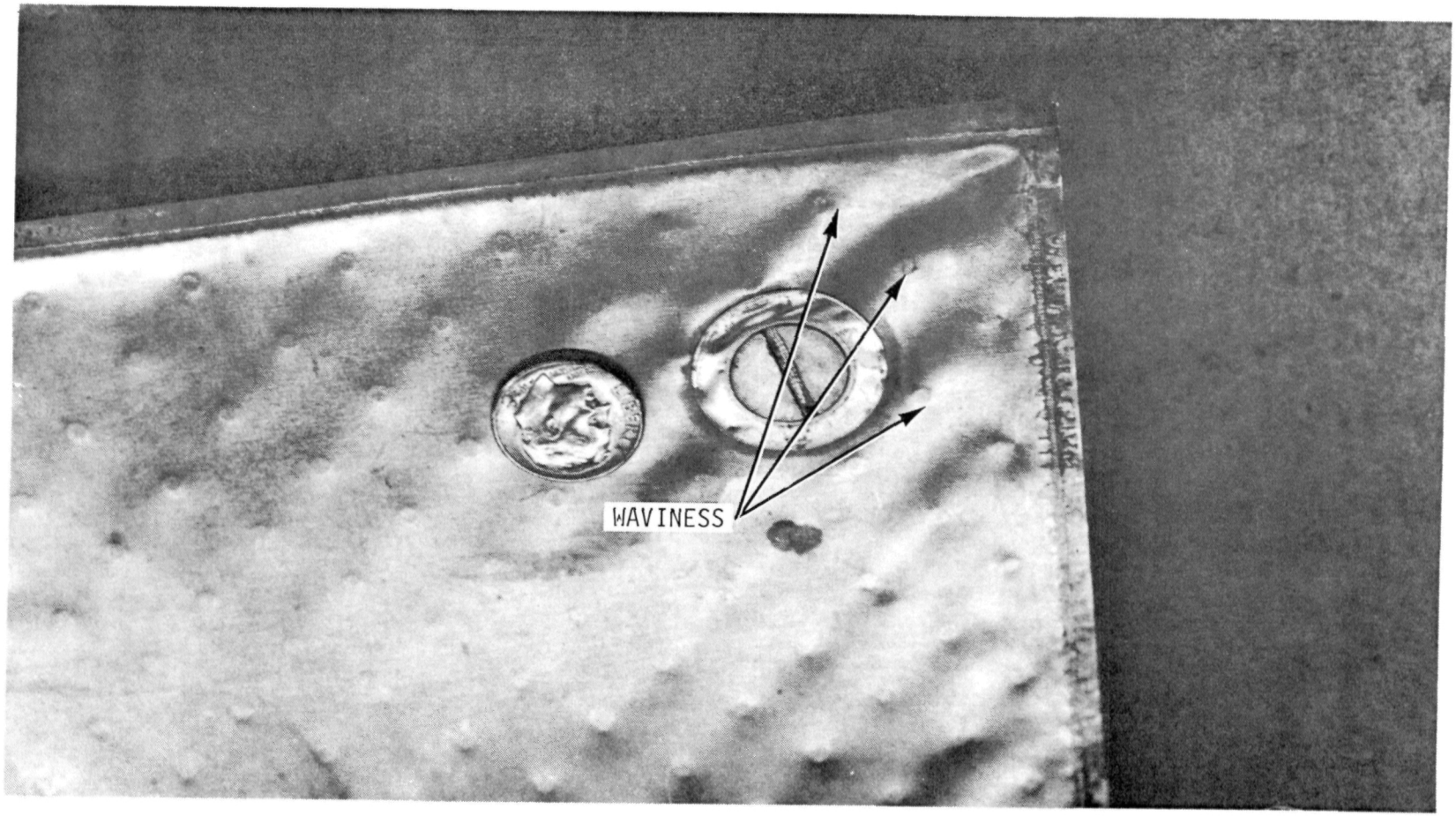


Figure 38. Waviness of Top Skin to 0.33mm (0.013 inch) Deep

Figure 39. A Small Opening at the Intersection of Edge Closures and Skin was Closed with a 0.08mm (0.003 inch) by 5mm (0.2 inch) by 8mm (0.3 inch) Patch Resistance Welded Over the Opening

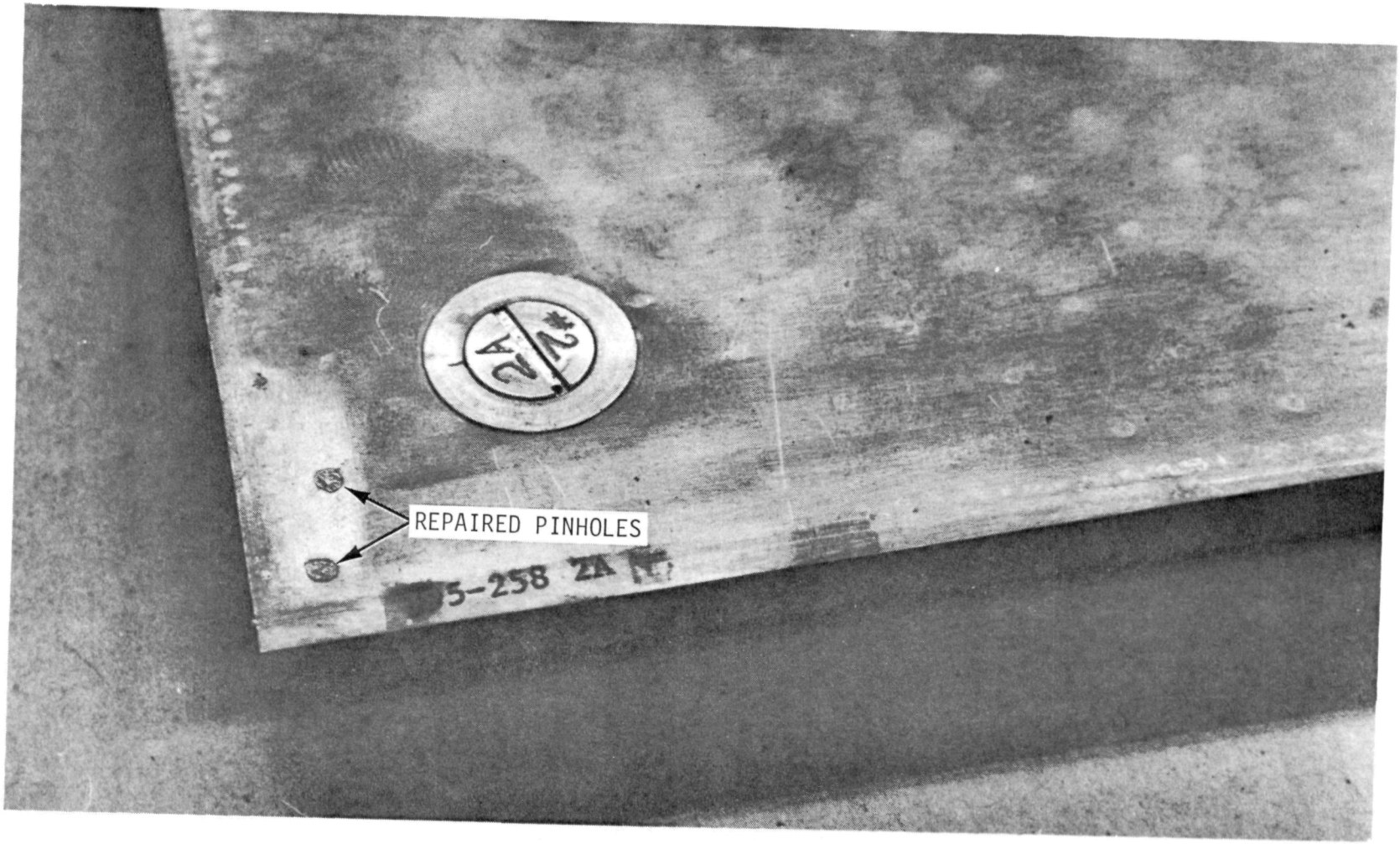


Figure 40. Repaired Pin Holes (Caused by Resistance Tack Welds During Layup for LID Bonding)

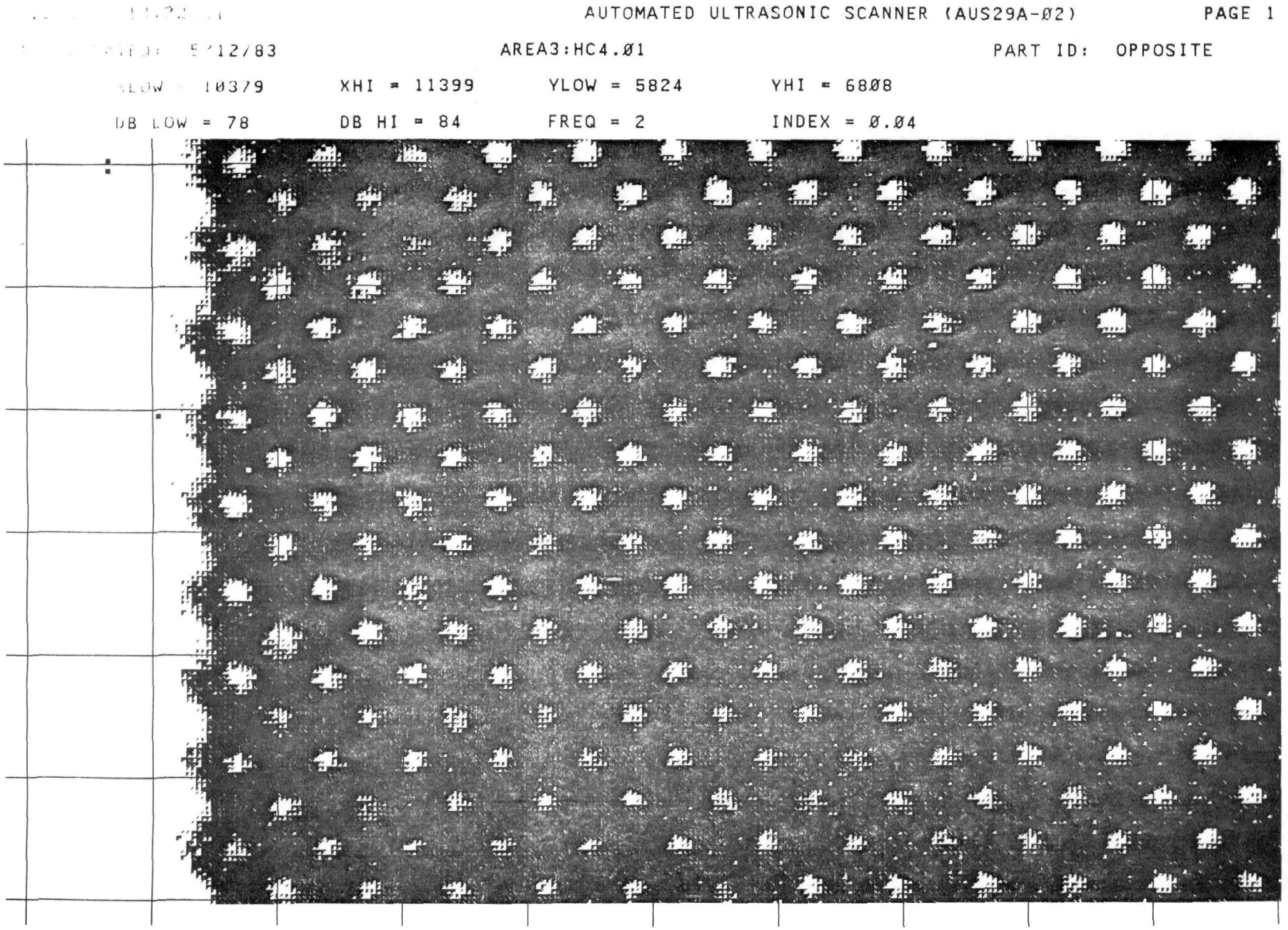


Figure 41. Through Transmission Printout from Automated Scanner Shows only the Alternating Nodes in Vacuum Tight Panel.

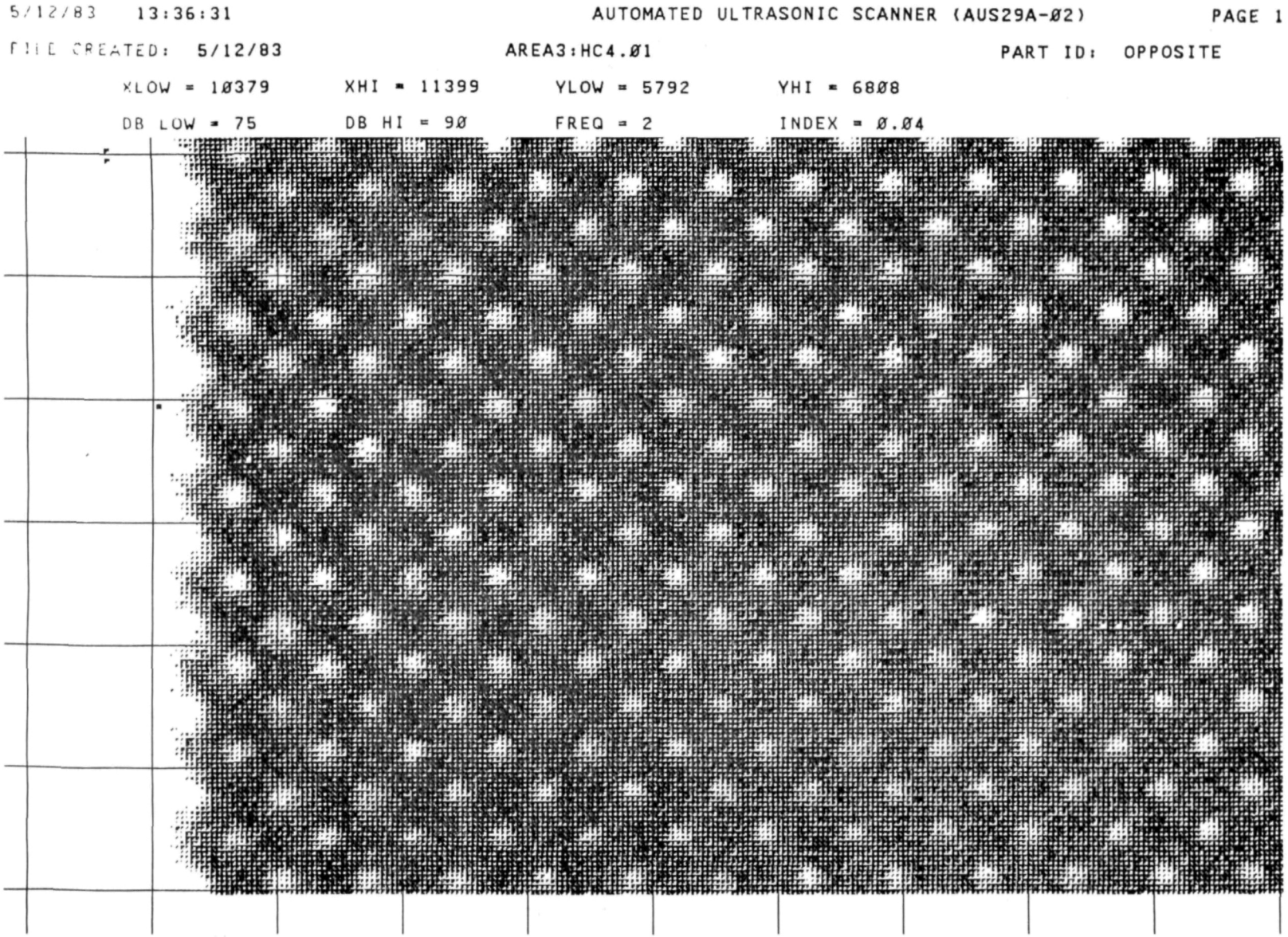


Figure 42. Through Transmission Printout from Automated Scanner Shows only the Alternating Nodes in Vacuum Tight Panel.

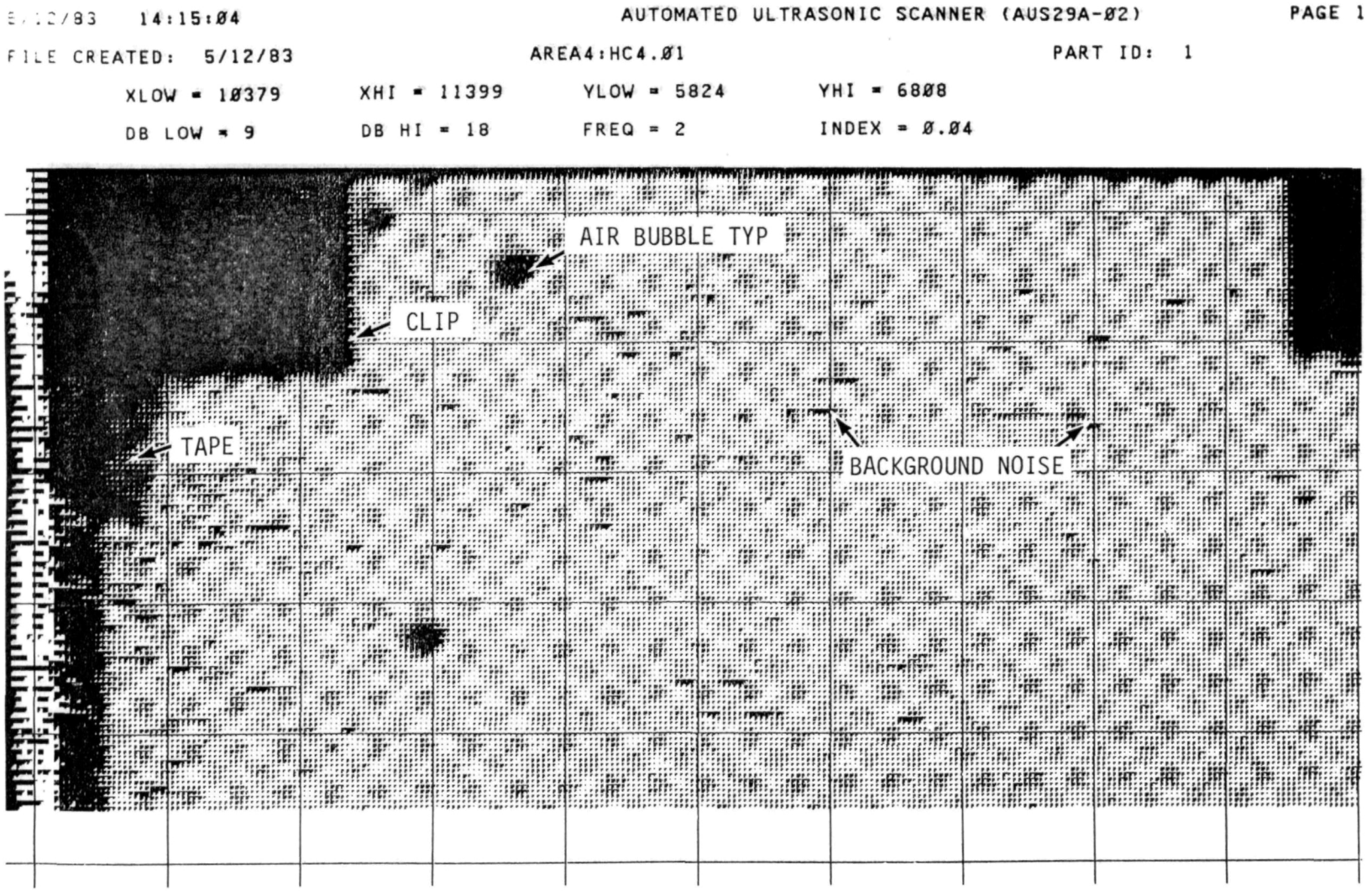


Figure 43. Ultrasonic Through Transmission Printout from Automated Scanner. The Light Area Represents Node Bonds. DB LOW = 9 Equals the Energy Sound Level Within the Panel.

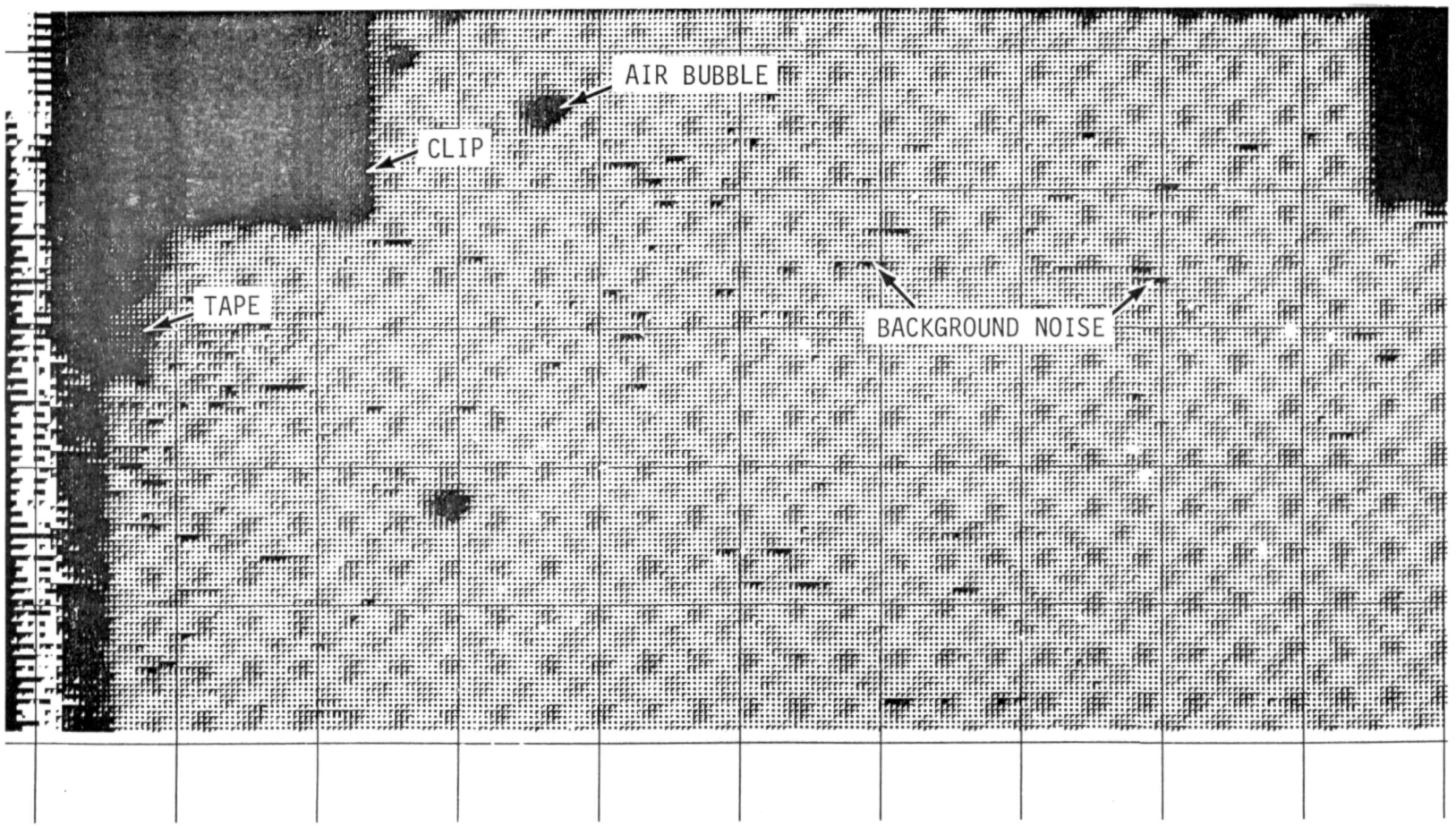


Figure 44. Ultrasonic Through Transmission Printout from Automated Scanner. The Light Area Represents Node Bonds. DB LOW = 8 Equals the Energy Sound Level Within the Panel.

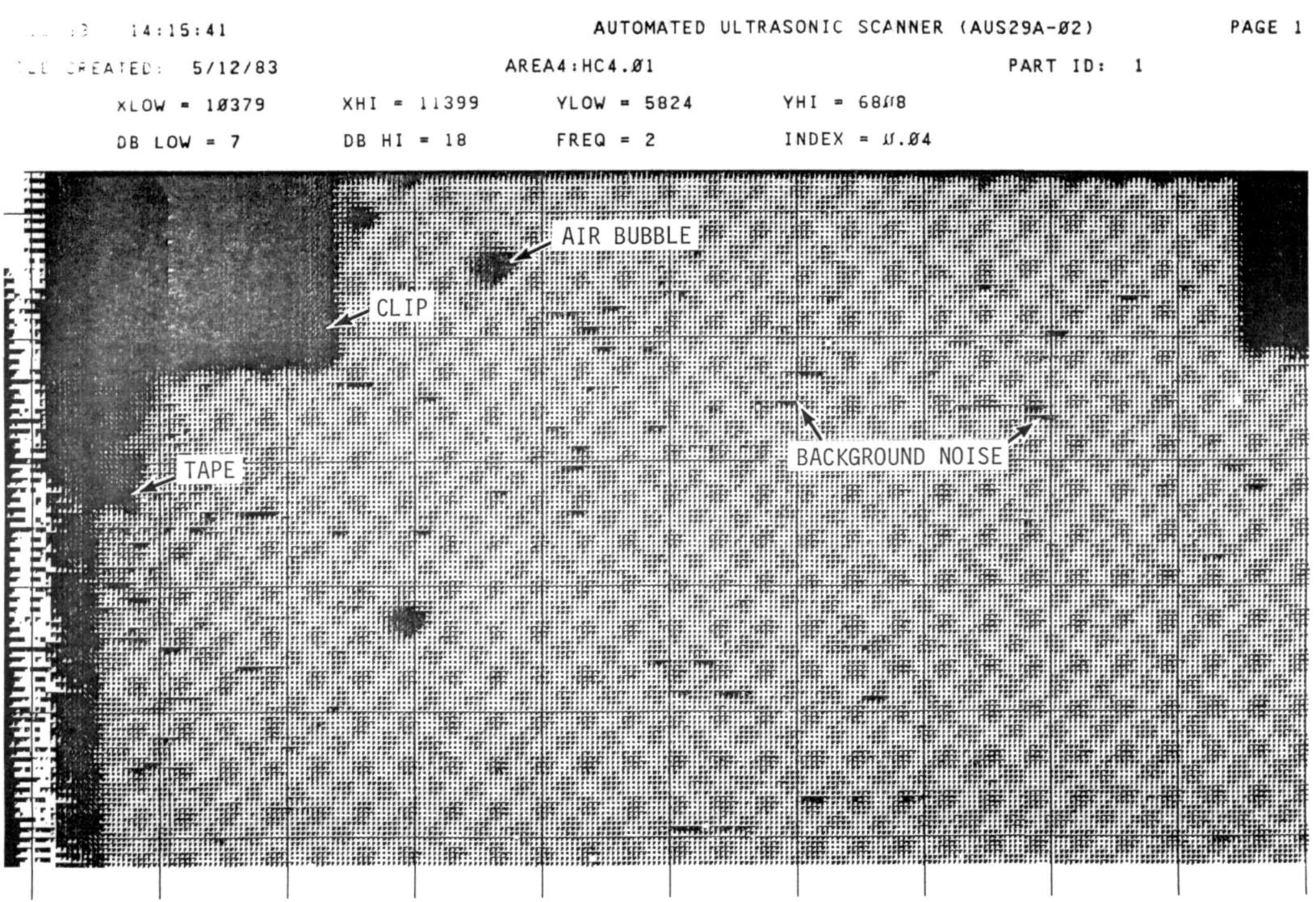


Figure 45. Ultrasonic Through Transmission Printout from Automated Scanner. The Light Area Represents Node Bonds. DB LOW = 7 Equals the Energy Sound Level Within the Panel.

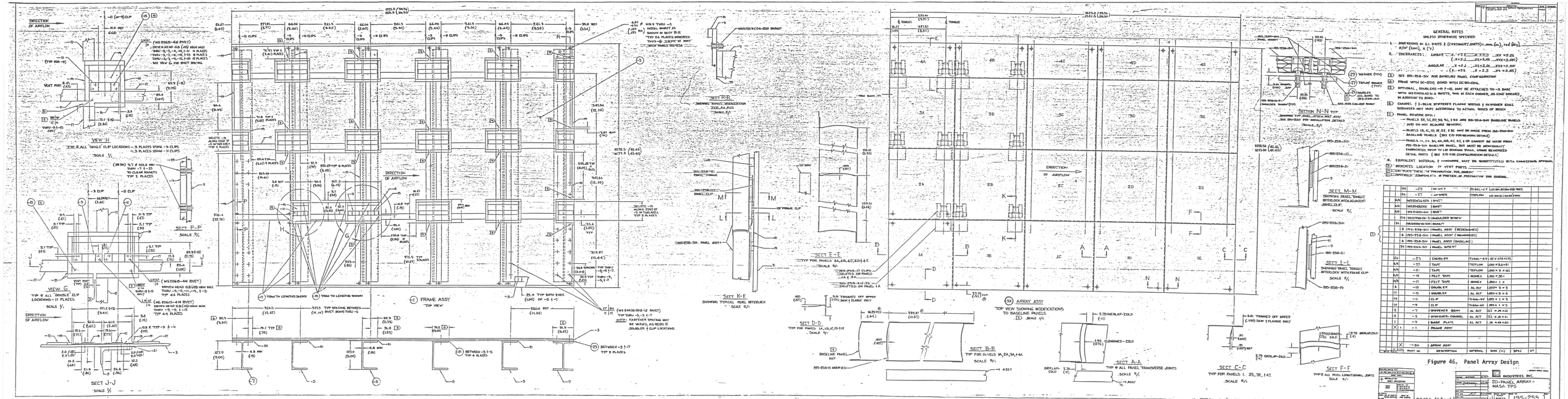


Figure 46. Panel Array Design

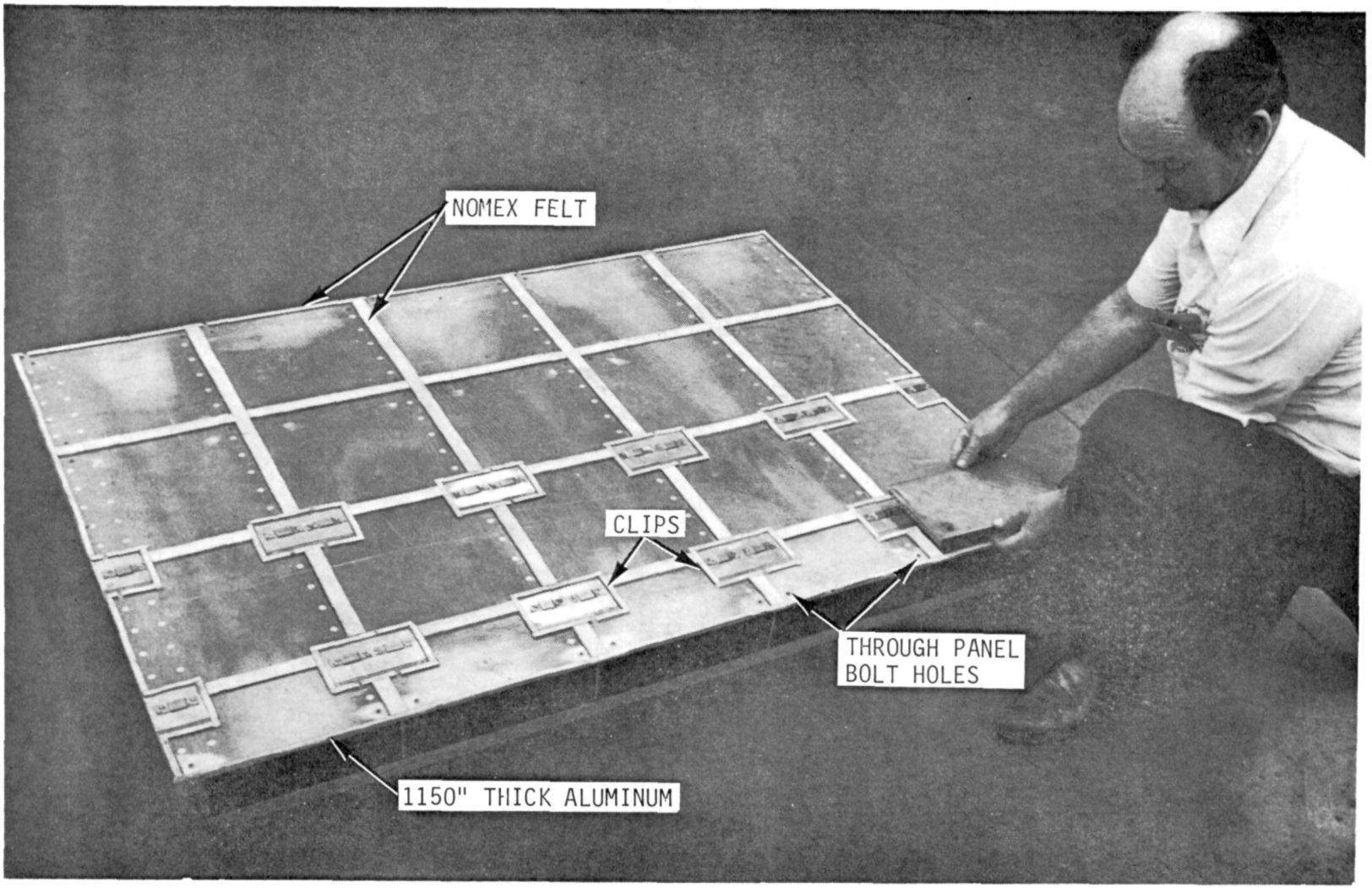


Figure 47 Holder for Task VI Titanium Multi-Wall 20-Panel Array

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Langley Technical Monitor: John Shideler
Interim Report

16. Abstract

The Titanium Multi-wall Thermal Protection System (TPS) panel was re-designed to incorporate Ti-6-2-4-2 outer sheets for the hot surface, ninety degree side closures for ease of construction and through panel fasteness for ease of panel removal. Thermal and structural tests were performed to verify the design. Twenty-five panels were fabricated and delivered to NASA for evaluation at Langley Research Center and Johnson Space Center.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
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